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EXPLOSAFETM INSTALLATION DESIGN

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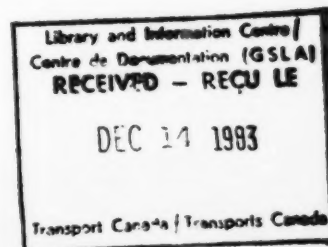
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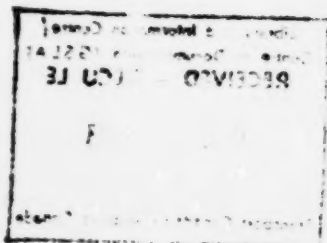
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17. Résumé Ce rapport donne un compte-rendu d'un project entrepris afin d'étudier et, possiblement, résoudre les difficultés techniques associées à l'installation du système de protection EXPLOSAFE à l'intérieur de wagons-citernes, dans le but de prévenir les ruptures thermiques et la combustion incontrôlée. Certaines considérations techniques, telles que la corrosion du matériel EXPLOSAFE et l'éclaboussement du liquide dans le wagon, présentent des problèmes sérieux. Des études plus détaillées s'avèrent nécessaires pour déterminer quantitativement la sévérité de ces facteurs. Les considérations économiques indiquent que les coûts initiaux et d'opération du schéma d'installation proposé seront élevés, comparativement aux coûts associés avec les wagon-citernes courants, équipés de calorifugeage ordinaire. Des efforts considérables (planifiés dans cette étude) seront requis pour vérifier le concept de montage choisi pour la production, mais les résultats de ces efforts promettent de bénéficier d'autres applications du système de protection EXPLOSAFE. En modèle du comportement thermique du wagon-citerne (de précision vérifié) devrait contribuer au développement de certains détails du concept d'installation.		
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EXECUTIVE SUMMARY

The transportation of dangerous cargoes such as liquid propane gas (LPG), anhydrous ammonia (AA), etc. creates the potential for a transportation accident such as the derailment of a tank car to become disastrous, particularly if the accident results in the tank car being engulfed in fire. Such external fires weaken the tank wall, while at the same time boiling the tank contents. At some point, the internal pressure build-up from the boiling may exceed the wall strength causing a sudden shell rupture, releasing a large volume of inflammable material to the fire and creating a massive "explosion-like" fire ball. Such an event, properly termed a thermally induced rupture and uncontrolled burn off, could be devastating if it occurred in an inhabited area.

EXPLOSAFE, an expanded aluminum foil, has shown promise in preventing the above phenomenon in 1/5 linear scale tank car flame engulfment tests.

The temperature and pressure rise of a tank lined with EXPLOSAFE can be delayed through the capability of the material to distribute the heat throughout the bulk of the cargo liquid.

This report, prepared by Davis Engineering Ltd., focuses on overcoming the practical engineering problems associated with lining the interior of full size rail tank cars with an annular layer of the aluminum EXPLOSAFE material, for operation in a rail transportation environment.

The acquisition and evaluation of available information pertaining to the EXPLOSAFE material itself, rail tank cars, and the various in-service conditions have led to a definition of design requirements and a conceptual design for an EXPLOSAFE installation.

Prior to describing the proposed installation design, a review and discussion will be given here of the aspects of the installation which are viewed as potential problems.

In spite of a comprehensive literature search, the severity of the effects of fluid sloshing within the tank car on an EXPLOSAFE installation, could not be determined because of a lack of applicable data. A preliminary investigation, and industry experience with fluid sloshing indicate that fluid sloshing loads could be of a critical nature. Test procedures by which to quantify these effects have been devised and are documented in the report as part of a concept deployment test program.

Two closely related problems are corrosion and tank cleaning. The impact of both on the EXPLOSAFE installation is largely dependent upon the ability to control the ingress of impurities into the tank car. There was no available corrosion behavior data for the reference EXPLOSAFE aluminum alloy (3010) in either the LPG or anhydrous ammonia loadings. Again, a test program to obtain the required data is described in the report. Corrosion rates from tests of an AA 3003 alloy in anhydrous ammonia were available however. If these rates are assumed to be applicable to AA 3010 EXPLOSAFE, a 114 mm layer of the material would lose thermal wall contact in a tank car in a period of approximately 14 months due to corrosion.

The cost of the cleaning process of the tank cars, and its constituent operations of steaming, drying and mopping up, would increase due to initial capital investment, increased level of effort and increased cleaning frequency for an EXPLOSAFE-equipped car. The cleaning process must be modified not only to make it function with an EXPLOSAFE-equipped car but also to prevent contaminating the car. If however, a substantial portion of the tank impurities are brought in with the loadings, as opposed to an accumulating concentration build-up with use, more frequent cleaning would be less effective since contamination would occur with the introduction of the first lading.

A description of the over-the-rail load spectrum and ensuing fatigue analysis would be important inputs to a final design. This information, since it is largely specific to a particular track and railcar type would have to be measured directly. A procedure to obtain this data is outlined in the report.

The 1/5 scale tests showed car shell temperatures of approximately 540°C which is below the melting temperature of the EXPLOSAFE material (650°C). There is some question however, whether a prolonged engulfment fire on a full scale tank would produce similar or much higher temperatures. Further, a torch fire impinging on the vapour section of the tank could conceivably also produce higher temperatures. The vapor regions of the tank are critical since the heat can be dissipated only through vapour convection and conduction along the tank car wall, and not through the liquid. If the EXPLOSAFE material were to melt, little or no thermal protection would be offered at the point of heat application.

Based upon the definition of design requirements resulting from the study results, a mechanical support system for the EXPLOSAFE has been designed. The concept was selected as the most suitable among 9 originally proposed candidates. The design was formulated with the knowledge that many of the problem areas identified are yet unresolved. A design contingency has been provided however, to shield the EXPLOSAFE by means of protective sheeting. This configuration would be adopted for example, if the sloshing loads were found to be excessive. Designs are provided for 114 mm and 305 mm EXPLOSAFE layer thicknesses to provide a degree of flexibility and also to provide some knowledge of the effects of layer thickness on the design. It is anticipated that the optimum layer thickness would be determined from a thermal analysis. The design allows a retrofit installation of the EXPLOSAFE system in an existing tank car or the integration of the installation with the production of a new tank car.

The basic design involves a support skeleton comprised of circumferentially expanded steel rings of preformed standard "T" section which are fitted against the internal tank wall. Longitudinal supporting rods are passed through the webs of the rings to compress the EXPLOSAFE against the wall. The EXPLOSAFE is supported in the elliptical end caps by means of standard "T" section preformed into domed caps. The design allows for all irregularities and dimensional tolerances of the tank.

A cost effectiveness analysis of the installation design was performed over a 20 year life cycle. The total cost is largely dependent upon EXPLOSAFE replacement interval and EXPLOSAFE layer thickness. For a 114 mm layer thickness and assuming a 5 year EXPLOSAFE replacement interval, the 20 year life cycle cost to retrofit and operate a tank car is \$96,500.00. The actual cost would be far greater if the EXPLOSAFE must be replaced every 14 months due to corrosion (i.e. approximately \$270,000.00).

As previously stated, a test program has been devised and costed which would conclusively determine the suitability of an EXPLOSAFE tank car installation from corrosional and mechanical standpoints. The program would be conducted in two stages. Two problems which would have to be resolved prior to conducting full scale tests are the verification of the sloshing loads and substantiation of the estimated corrosion rates. These items would be addressed in the first stage by a supplemental test program which would then be followed by full scale impact and over-the-rail testing in the second stage. The latter stage would be conducted only if it is not precluded by negative test results during the first stage. The total cost of the three year test program is estimated at \$789,600.00.

At the time of this writing, no thermal model or full scale fire test has revealed conclusively that EXPLOSAFE in rail tank cars is functional thermally and offers advantages over the apparently successful current method of exterior tank car insulation. After consideration of the above, and the technical difficulties and high costs associated with the intallation of aluminum EXPLOSAFE mesh in rail tank cars, it is the opinion of Davis Engineering Limited that the concept should not be pursued.



1.0 INTRODUCTION

This study was conducted for the Transportation Development Centre of Transport Canada under contract number OSD82-00065 by Davis Engineering Limited in association with the Whiteshell Nuclear Research Establishment and PROCOR Limited.

The transportation of dangerous cargoes such as propane (LPG), liquid natural gas (LNG), aviation fuels, etc. creates the potential for transportation accidents, such as the derailment of a tank car, to become disastrous particularly if the accident results in the tank cars being engulfed in fire. Such external fires weaken the tank wall while at the same time boiling the tank contents. At some point, the internal pressure build up from the boiling may exceed the wall strength and the wall may rupture suddenly, releasing an "explosion-like" fire ball. If this should happen in a built-up area, the results could be devastating. While such an event is most properly termed a thermally induced rupture and uncontrolled burn off, it is most commonly called a BLEVE or boiling liquid expanding vapour explosion.

In recent years, tank cars have undergone modifications by the inclusion of shelf couplers, head shields and external insulation. These modifications have demonstrated their effectiveness in the November 1979 derailment at Mississauga, where several retrofitted tank cars carrying LPG were involved in a post-derailment fire environment, but did not result in a BLEVE release. It was also noted that head punctures were avoided on cars fitted with head shields, but did occur on tank cars not so fitted, and there was general agreement that car separation was minimized due to the retrofit of double shelf couplers.

An alternative approach to external insulation of tank cars was proposed by the EXPLOSAFE Corporation, a division of Vulcan Industries, to use their explosion suppression product EXPLOSAFETM.

According to an EXPLOSAFE Corporation brochure (19), the EXPLOSAFE material functions using two main mechanisms.

"Quenching the reaction by dividing the container into minute cells which inhibit flame propagation is one way. Another is to absorb the heat released during the reaction with a porous filler mass of high heat absorptivity".

Concerning BLEVE's, "The EXPLOSAFE system has demonstrated a potential for preventing or delaying such ruptures by reducing the wall temperature. In the case of local heat exposure, the rise in pressure can also be delayed through the capability of the system to distribute heat throughout the bulk of the liquid and reduce the intensity of localized boiling".

The EXPLOSAFE system has been tested using 1/5 linear scale LPG tanks at CFB Suffield and has appeared to be successful.

The success of the 1/5 linear scale test program has prompted Transport Canada to enter a second phase research program to further develop the heat diffusion technique and bring it to a stage where it can be successfully deployed. This program aims at overcoming the practical engineering problems of using the material in an operating rail transportation environment; problems such as corrosion, cleaning of the cars, maintenance of wall contact, etc. These problems need to be addressed to a sufficient degree to ensure that they can be solved and to develop a realistic pre-production configuration of the EXPLOSAFE system to use in full scale testing. An analytical thermal model is being

developed under a separate contract which can help to explain the complex mechanisms which occur prior to a BLEVE and to provide some input into the EXPLOSAFE installation design (eg. thickness of EXPLOSAFE annulus).

The specific objective of the project described in this report was to develop a program of engineering analysis and testing aimed at designing a prototype installation for the EXPLOSAFE material in a rail tank car. The design is to consider the various elements of the rigorous environment and other associated practical difficulties. Among the design objectives in the study were the following items:

- support an annulus (114 mm to 305 mm thick) of the EXPLOSAFE material in close contact with the inside of the tank wall with the assumptions that the tank is exposed to an external heat source and that the principal heat path is circumferentially around the tank.
- the installation will be capable of maintaining the effectiveness of the EXPLOSAFE material over the 20-40 year service life of a rail tank car in the presence of the forces and vibrations experienced by a tank car during routine rail operations.
- be capable of surviving the severe internal temperature environment created within a rail tank car by external heating.
- minimize the added weight of the rail car and the volume of cargo displaced by the installation system.
- permit the interior tank shell and heads to be examined for evidence of damage that would reduce the pressure retaining integrity of the shell.

- permit the tank car to be cleaned when its use is switched between anhydrous ammonia and LPG.
- protect against corrosion due to chemical action and/or mechanical wear.

The design installation is shown conceptually in Figure 1.

This report is structured in the following manner.

Section 2.0 investigates the various elements of the overall operational conditions and problem areas leading to a definition of the design requirements. Section 3.0 identifies those areas in which insufficient information was available to provide a thorough assessment. Section 4.0 presents a postulation of changes in the operational procedures that could result from the implementation of the EXPLOSAFE installation into the rail tank car fleet. Section 5.0 investigates several conceptual support systems and provides some rationale for the selection of a particular design. Section 6.0 compares the life cycle costs of various installation designs. Section 7.0 discusses the results of the activities investigated in Sections 2.0 through 6.0, and how they impact on the EXPLOSAFE installation concept. Section 8.0 plans programs which should be conducted prior to implementing the EXPLOSAFE installation on a production basis. Section 9.0 draws conclusions and makes recommendations which the investigators felt were appropriate for the on-going activities of the overall program.

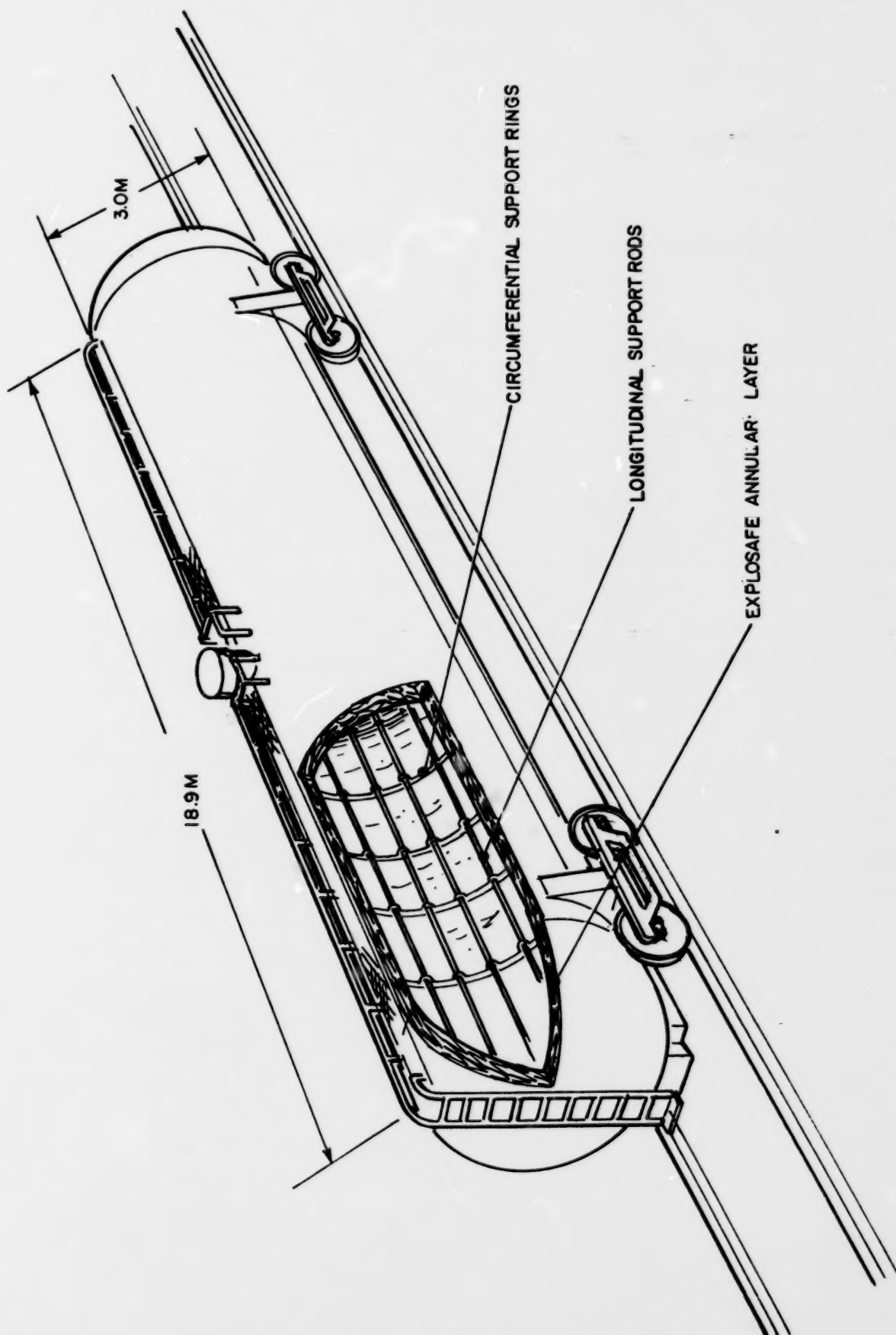


Figure 1 EXPLOSAFE INSTALLATION IN TANK CAR

2.0 DESIGN CRITERIA AND REQUIREMENTS

2.1 Rail Tank Car Fleet

The rail tank car, when first introduced over a century ago, was designed for the transportation of crude oil and petroleum products. Today in the U.S., approximately 12 percent of the national freight car fleet is comprised of tank cars. These cars are governed by guidelines issued by the Association of American Railroads (AAR) and the American Department of Transportation (DOT). Due to the wide variety of products transported and their varying requirements, there exist several DOT and AAR tank car classifications. Of these, two types are utilized in Canada for the transportation of inflammable gases. The following excerpts from the AAR Manual of Standards and Recommended Practices, Specification M-1002, describe these two classifications.

Class DOT-105A,J or S***W tank cars are insulated carbon steel pressure cars, with a manway nozzle, designed for top loading and unloading; bottom outlet or washout prohibited. Class 105A or J***ALW tank cars are similar except that they have aluminum alloy tanks. Class 105A***F has forge welded tanks.

A = equipped with top-and-bottom shelf couplers

J = equipped with jacketed thermal protection, tank head puncture resistance and top-and-bottom shelf couplers

S = equipped with tank head puncture resistance and top-and-bottom shelf couplers

Class DOT-112A,J,S, or T***W tank cars are insulated carbon steel pressure cars, with a manway nozzle and without bottom connections, designed for top loading and unloading. They are designed for loading of liquefied compressed gases or flammable liquids.

- A = equipped with top-and-bottom shelf couplers
- J = equipped with jacketed thermal protection, tank head puncture resistance, and top-bottom shelf couplers
- S = equipped with head shields and top-and-bottom shelf couplers
- T = equipped with non-jacketed thermal protection system, top-and-bottom shelf couplers, and head shields

Note: Class 112A,J,S, or T***F tank cars are similar except they are forge welded tanks from Class ICC-105A.

The Canadian owned tank car population permitted to carry these dangerous commodities, has been determined in order to more fully describe the impact of a car modification. As of April 1981 there were 4424 such cars in existence with an annual new car production rate of 200(1). The breakdown was as follows:

- Type 112:	3831 cars
- Type 105:	
(approximately 25% of	
2373 total cars used	
for inflammable gases)	<u>593-cars</u>
Total	<u>4424 cars</u>

The annual production rate is based upon trends of the past 15 years and it cannot be stated for certain whether these trends will continue. There are cars operating in Canada however, which

are not Canadian owned, yet may be subject to Canadian regulations. The U.S. tank car population is approximately ten times that of Canada and some of these would operate occasionally in Canada.

2.2 In-Service Conditions

The environment to which the EXPLOSAFE would be exposed has been defined insofar as information is available from existing data. Normal practice is to obtain the data for the particular set of conditions required.

The dynamic loading has been described for impact considerations. The peak impact loading expected during the life of a tank car can be taken as 4g longitudinally, 0.5g laterally and 2.5g vertically. This set of conditions has been supplied by PROCOR as the approximate dynamic tank car loading criteria, based upon experience. These loading criteria were also used for the design of the EXPLOSAFE and its support structure. During the latter stages of the design, there was some concern expressed that actual impact/humping loads could exceed the longitudinal loading criterion used. One can relate the design loading of the EXPLOSAFE structure to the design and test specifications for the rail car. AAR Specification M1001, Vol. 1, states that fully laden tank cars must undergo impact tests with an impact car velocity of up to 22.5 Km/hr (14 mph) or until a coupler force of $5.56 \times 10^6 \text{ N}$ (1,250,000 lb) is reached. The maximum weight as seen by the rails of a fully laden tank car is $1.17 \times 10^6 \text{ N}$ (263,000 lb). This, translated into a 'g' loading, is $5.56/1.17 = 4.75 \text{ g}$. Although this value is somewhat in excess of the design loading used, the design can be considered safe since large factors of safety are utilized. In addition, experience has shown that mechanical components can withstand short duration impact loading of greater magnitudes than would normally be expected to yield the material (i.e. greater strength at high strain rates).

The tank car is also subject to vibration caused by such things as irregularities formed where rail sections meet and other complex vibrational patterns. One known effect involves the flexing and distortion of the tank shell due to the various loading combinations. These conditions, which constitute a fatigue environment, are largely dependent upon the characteristics of the vehicle and the track. Specific recommendations are made to quantify the fatigue environment for the relevant transporting conditions in Section 8.3.

Some EXPLOSAFE fatigue data is available from previous vibration tests which have been performed. These tests were performed to assess the performance of EXPLOSAFE in an aircraft fuel tank application. The test program involved a combined sloshing/vibration test and vertical vibration tests of a laden tank under the following conditions:

Slosh/Vibration +/- 15° tilt from horizontal @ 0.33 hz with
 +/- 2 g vertical acceleration @ 33 hz

Vertical Vibration: +/- 2g @ 25 hz
 +/- 7g @ 100 hz
 and +/- 20g @ 500 hz

The above tests showed no appreciable damage to EXPLOSAFE or tank. Since the tanks used in the tests were full of EXPLOSAFE and since the effects of scale could be considerable, the sloshing results cannot be applied directly.

Over-the-track results for a 90 metric ton tank car from St. Louis to Kansas City showed average vertical accelerations measured at the bolster of approximately 0.2g (1.8 g peak) at a dominant frequency of 5 hz (3).

Since the vibration test conditions in the aircraft installation experiment were more severe than the road environment, it can be stated that fatigue of the EXPLOSAFE material itself should not be a prime concern due to vibration alone. The vibration could, however, be problematic to the EXPLOSAFE support structure. This concern is addressed in a later section.

There are certain thermal environments to which a tank car may be exposed, which must be considered. One severe temperature environment to which the EXPLOSAFE would be subjected, is that imposed by a pool fire during an accident. Some 1/5 linear scale pool fire tests performed have shown the maximum tank surface temperature to be approximately 540°C (4). Although this is below EXPLOSAFE's melting temperature of 650°C , there remains some uncertainty as to whether the same tank temperatures would be reached in a full scale tank subjected to a prolonged fire.

A localized torch fire impinging on the top of the tank in the low-conducting vapour region could cause local temperatures beyond those imposed by a pool fire and melt the aluminum mesh. No relevant test data was available however at the time of this writing. Certainly, if the melting temperature of the EXPLOSAFE were exceeded, the material would cease to transfer heat away from the point of application and provide very little, if any thermal protection in the critical area.

Assuming that the EXPLOSAFE layer is intact, thermal expansion would not cause any reduction in wall contact, nor is the material particularly sensitive to large temperature gradients. In fact since aluminum expands thermally at a greater rate than steel and the gap between the support structure (steel) and the tank shell (steel) must remain the same, elevated temperatures would essentially act to compress the EXPLOSAFE against the wall and enhance its thermal action.

A secondary thermal consideration is thermal shock caused by loading and unloading of the ladings. In the absence of vapors, when an evacuated tank is loaded with LPG for example, the evaporation cools the tank very rapidly. This temperature variation is not sufficient to thermally stress the EXPLOSAFE to failure in one application, however repeated applications could cause thermal fatigue. Further investigation would be required in this area.

The lading temperature within the tank varies seasonally during normal operation from approximately -40°C to 60°C .

The amount of lading permitted in a tank car carrying an inflammable gas is prescribed by two criteria. One is maximum weight of the vehicle at the rail, which is $1.17 \times 10^6 \text{N}$ (263,000 lb). The second criterion is specific to the commodity carried. For each commodity, a maximum percentage is defined in terms of the weight of gas in the tank divided by the weight of water the tank will hold at 15.6°C (60°F). The second criterion ensures that adequate space is left for thermal expansion. Canadian Transport Commission (CTC) regulations for the transportation of dangerous commodities by rail, state that the percentage as defined above is 46% for LPG and 57% for anhydrous ammonia. In both cases, the tank is approximately 90% full by volume. On some occasions however, tank cars are known to carry less than the maximum allowable amount of lading. Although this condition occurs infrequently, it is a design consideration nevertheless.

Dynamic forces on the EXPLOSAFE due to fluid slosh are very difficult to quantify and yet could be of a critical nature. The sloshing forces are expected to be of a greater magnitude than the inertia forces due to the mass of the EXPLOSAFE itself and therefore could possibly govern the design of some aspects of the support structure.

The forces from sloshing are examined in a preliminary way in Section 3.2. Recommendations are made concerning analytical and experimental studies to determine the magnitudes of these forces. A full scale slosh impact test is also devised and costs projected in Section 8.3.1.

The corrosion performance of the EXPLOSAFE material has been evaluated as described in Section 2.5. The cleaning process has also been reviewed and is described in Section 2.6. Supplemental and full scale test programs for both the corrosion and cleaning aspects are outlined in Section 8.0.

2.3 Definition of EXPLOSAFE Properties

The following properties of EXPLOSAFE have been defined:

Material:	AA3010 aluminum, 0.076 mm (.003 in) foil
Density:	46.9 Kg/m ³ (2.9 lb.ft ³)
Yield strength (EXPLOSAFE):	4.8-6.2 kPa(g) (0.7 to 0.9 psig) depending upon orientation
Young's Modulus:	97-131 kPa(g) (14 to 19 psig) depending upon orientation
Thermal conductivities (5):	perpendicular to layers 0.25 W/m °C parallel to layers along minor diamond axis 0.50 W/m °C parallel to layers along major diamond axis 3.03 W/m °C

- This report assumes that, to maximize the thermal mechanism, EXPLOSAFE should be oriented in the tank with layers concentric about the longitudinal tank axis so as to provide maximum circumferential heat transfer.

- Failure of the EXPLOSAFE material can be defined as 5% deformation, since this level represents the onset of plastic deformation. Beyond this limit, the EXPLOSAFE would not return to its original position.

2.4 Mechanical Parameters

The following mechanical parameters have been defined:

Tank car:

- 18.9m (62') long x 3.0m (10') diameter
- 2:1 elliptical heads
- TC 128 steel construction with 16 mm wall

EXPLOSAFE:

- 114cm (4.5 in) thick annular ring oriented to maximize circumferential heat transfer
- qualitative consideration is also given to the effect on the cost of the installation of varying the thickness
- 4.8-6.2 KPa(g) (0.7 to 0.9 psig) maximum contact pressure

Support System:

- the support structure design criteria and specifications are given in Section 5.0.

2.5 Corrosion Processes

The extent of corrosion on EXPLOSAFE foil, when used for tank car applications, is likely to be determined mainly by the presence of impurities in the ladings. In high purity anhydrous ammonia (A.A.), at ambient temperatures, the general corrosion rate is unlikely to exceed a few m.a^{-1} (fraction of one mil per year). Galvanic contact between the aluminum mesh and the steel tank car surface would not be expected to change this. However, the presence of small quantities of water (fraction of one wt.%) in A.A. could result in a significant increase in the rate of corrosion of aluminum in contact with steel. Metal loss rates of $50 \mu\text{m.a}^{-1}$ (2 mpy) could occur, and on the very thin EXPLOSAFE with a mesh cross-section $75 \mu\text{m}$ (3 mil), these rates would cause rapid penetration. Other contaminants, such as alkali metal chlorides, are also likely to increase the galvanic corrosion rate on aluminum. The occurrence, simultaneously, of water and chloride in A.A. would probably have an additive effect on the corrosion rate. The pressure of contaminants would also cause an increase in the rate of fretting corrosion on the EXPLOSAFE mesh in contact with the tank car surface.

The corrosion in LPG will also be affected by the presence of impurities in the ladings. In LPG, any water present is likely to exist as a separate phase, with impurities such as chlorides favouring the aqueous phase. Therefore, the corrosion problem is similar to that of corrosion in an aqueous chloride environment with the supply of oxygen being controlled by its availability in the LPG. On this basis therefore, corrosion should be localized to regions at the bottom of the tank car where this aqueous phase would separate out.

Although the precise corrosion rates cannot be deduced without a precise knowledge of the amount of impurities present, there are

some operational factors which may be significant (7). U.S. Department of Transportation Specification Title 49, paragraph 173.315, states that cargo tanks of quenched and tempered steels carrying anhydrous ammonia must carry a minimum of 0.2 wt% water. This is also standard practice in Canada, and its purpose is to prevent stress corrosion cracking of the tanks. With regard to LPG, the industry standard for the maximum allowable level of free water in LPG ladings is 0.001 wt% (25 ppm) at the shipping point. If this standard is met, corrosion should not be significantly enhanced by the presence of water. There has however been some evidence of extra water, the source of which is unknown, which could increase corrosion rates. An additional consideration is the method of off-season LPG storage utilized. Current practice is to drill large salt beds to form salt caverns. The LPG is stored in these caverns during the summer months by flotation on brine. There is a potential salt contamination problem when the LPG is retrieved. This salt, if present, could greatly increase corrosion rates.

Cleaning and drying of the tank cars between ladings could result in accelerated corrosion of both the aluminum mesh and the tank car surface which is in contact with the mesh.

There are several factors which would contribute to corrosion during the cleaning and drying operation, and these are listed below:

- a) Elevated temperatures (up to 160°C) are used in these operations.
- b) Drying of the hot surfaces with air ensures the presence of excess oxygen at wet metal surfaces at elevated temperatures.
- c) Aggressive contaminants such as chlorides and sulphates are present in the cleaning water.

- d) Concentration by evaporation can result in very concentrated, aggressive, hot salt liquors being formed on metal surfaces.
- e) The convoluted structure of EXPLOSAFE would restrict mass-transport of steam during the evaporation stage, thereby prolonging final dry-out of these aggressive liquors. The extent of restriction cannot be determined without further testing.
- f) The contact between the aluminum and steel surfaces results in a rapid crevice corrosion of either the steel or aluminum (or both) during the elevated temperature phase of the cleaning/drying operation.

In carrying out the above assessment, as detailed in Appendix A, it became quite evident that there is insufficient data available on aluminum alloys, in A.A. and LPG environments, to deduce with any reasonable degree of certainty the corrosion behaviour of EXPLOSAFE mesh operating for extended periods in these environments. The effect of impurities present in the ladings must be understood better and particularly their effect under conditions of galvanic coupling of the mesh to steel. Also, the effect of temperature on the corrosion behaviour should be characterized.

2.6 Cleaning Process

The existing cleaning process was used as the reference. If this process was found to be incompatible with EXPLOSAFE equipped tank cars, alternative and undoubtedly more expensive procedures would be required, making EXPLOSAFE less cost effective.

The present cleaning process is an efficient and very importantly a simple one which is well defined but not rigid. There is sufficient flexibility such that the operation does not require

continuous monitoring or split-second timing of the various procedures. This flexibility is due to the simplicity of the object that is being cleaned; an 18.9 m long and 3.0 m diameter thick-walled steel tank. Using EXPLOSAFE would greatly change this, as it is a very complex structure and when placed in a tank along with its restraining mechanism, would produce a tank difficult to clean and readily damaged mechanically or chemically.

A detailed evaluation of the effect of EXPLOSAFE on the cleaning operation is presented in Appendix B. The following is a summary of those results.

The analysis showed that the existing cleaning process will remove the ladings from the surface of the EXPLOSAFE. However, as stated in Section 2.5, there is a problem with the effect of impurities on the corrosion processes which may occur within the tank. These impurities enter the tank during the cleaning process and likely with the ladings also. The present procedure is not capable of effectively removing these impurities. It is possible to modify the cleaning process to prevent it from contaminating the tank. Therefore if the ladings do not contain a significant amount of impurities, the tank would remain free of deleterious materials.

The use of EXPLOSAFE will affect the major processes of the cleaning operation (steaming, drying and mopping up) but it will have no affect on the flaring and water flush steps. The steaming time will be extended because of the greatly increased surface areas of the tank interior. In addition, there may be a possibility of stagnation of the vaporized ladings within the mesh in the furthest reaches of the tank, necessitating increased steam flows to assure their removal.

The present air drying procedure will not work, as the existing system would cause the tank to cool too rapidly forming

significant amounts of condensate within the mesh and the system flow velocities within the tank are insufficient to remove it. As well, the air quality is not controlled and could contaminate the mesh by introducing atmospheric pollutants. To dry the tank, the air must be cleaned, delivered at a controlled temperature and relative humidity and most importantly, be distributed within the tank at a sufficient flow rate to generate turbulence to assure speedy evaporatation of the condensate from the mesh.

The mopping-up operation would require the removal of a strip of EXPLOSAFE from the full length of the tank bottom, to allow removal of any crud or residual condensate. The removed mesh would have to be cleaned and dried outside the tank prior to replacement. This operation will require the use of three men rather than the usual two, and will probably take two hours instead of a half-hour. Normally, after mopping-up is complete, the tank interior is inspected for damage (cracks in welds etc.) but the layer of EXPLOSAFE will prevent this.

An additional concern regarding crud formation is the limited ability of the crud to settle from the walls in an EXPLOSAFE-lined car. The iron oxide formed on an unlined tank wall normally gravitates to the tank bottom due to its higher density and by washing of the crud from the wall. In the presence of EXPLOSAFE, the oxide production rate is not altered but its movement is impeded. Lading impurities may be entrapped along with the crud near the wall. The result will likely be less crud formation at the tank bottom but an increased amount at the EXPLOSAFE/wall interface. The presence of iron oxide itself on the surface of the aluminum mesh will not be a problem, however other impurities may act as described in Section 2.5. It is not envisioned that the above effect would cause any contamination of ladings in excess of the amount already present.

It is expected that the costs of cleaning will move from the \$700-800 range to the \$1000-1500 range per car because of the increased difficulty of the operation. In addition, the user would be subject to the extra costs required to maintain the EXPLOSAFE system.

The preceding changes were required as a result of EXPLOSAFE directly affecting a particular step in the process or the necessity to avoid introduction of deleterious material into the tank. A contaminated car could likely be cleaned using a combination of the modified present procedure and the use of a complexing agent. However, the further expense incurred by this method would make the tank cleaning significantly more expensive than estimated above. Therefore prevention is the most economical solution. However, if the loadings are major contributors of impurities then it does not matter how clean the tank is after cleaning, it will be contaminated with the first lading and the spectrum of corrosion processes outlined in Section 2.5 will occur.

2.7 Definition of Design Requirements

The completion of tasks 2.1 to 2.6 previously described has enabled the formulation of certain design criteria, based upon knowledge obtained to date, for an EXPLOSAFE-equipped tank car.

In general terms, the system must be as simple and inexpensive as possible to implement, operate and maintain, while still reducing the possibility of a tank rupture. The extra weight and volume added to the tank car should be minimized since this would otherwise be occupied by the lading.

The installation must be able to withstand any situation which could prevail during a derailment. A tank-engulfing pool fire or torch fire are environments which could result. Temperatures as

high as 540°C have been attained in one-fifth scale pool fires (4), and this temperature could conceivably be exceeded during a torch impingement fire. The melting points and thermal expansion properties of the design components are therefore important.

It has been found in previous sloshing tests (2), that if batts are oversized by 2% to 3%, the formation of voids due to excessive movement can be compensated for. Although the test fuel tanks were full of EXPLOSAFE, by analogy, a similar 2% to 3% compression of the matrix against the tank wall by the support system is recommended. At no point in the tank however, should the EXPLOSAFE material be compressed more than 5% since inelastic deformation begins at this level.

From a corrosional standpoint, the design should minimize the close contact of dissimilar metals leading to accelerated galvanic corrosion and pitting corrosion. The EXPLOSAFE batt compression here again should minimize movement and subsequent fretting corrosion.

The design will consider an EXPLOSAFE annular layer of 114 mm (4.5 in.) thickness. It was suggested by EXPLOSAFE Division of Vulcan Industrial Packaging Ltd. that complete filling of the tank with EXPLOSAFE was beneficial but not essential and that a thickness beyond 114 mm would not afford much extra protection. One design iteration was performed with a 305 mm (12 in) layer however, to quantify the effect on installation of cost varying the EXPLOSAFE layer thickness.

Many of the design criteria can be described as they relate to the EXPLOSAFE support system design. The primary function of the support structure is to maintain adequate contact pressure between the EXPLOSAFE and the tank wall.

The structure must withstand the static and dynamic loads imposed by its own weight and the weight of the EXPLOSAFE it supports. The directional tank accelerations, as previously mentioned, are 4g's longitudinal, 2.5g's vertical and 0.5g's lateral. These approximate the design and testing values used in the fabrication of tank cars. There is no point in using support structure design criteria which exceed those of the tank car shell, since mechanical failure of the tank car shell would render the EXPLOSAFE useless in any case. Further loads are caused by compression of the EXPLOSAFE against the tank wall. Any protuberances of the structure into the tank should be minimized since they are subject to fluid loads due to tank accelerations, and essentially act as baffles which restrain the movement of the adjacent fluid. Additional dynamic sloshing loads are imposed upon the structure directly and are also transmitted through sloshing loads on the EXPLOSAFE matrix.

Under the dynamic inertial loads described above, the EXPLOSAFE must be supported at a minimum of 3.8 m (150 in) intervals longitudinally. This will prevent the occurrence of vertical sag or longitudinal compression which would lessen EXPLOSAFE/wall contact. This support interval is due to the inertial loads only and not fluid effects.

Throughout the complete loading spectrum, the structure must not be allowed to deform by an amount sufficient to lessen wall contact area and thus prevent the thermal action of the EXPLOSAFE.

The installation of an EXPLOSAFE system will also have an effect on the structural integrity of the tank car. All loads on the support system and EXPLOSAFE must ultimately be supported by the tank wall and these represent loads in excess of those found in cars not equipped with EXPLOSAFE. As such, the weight of the support structure and the methods used to fasten it to the tank

wall become important considerations. Modifications to the tank wall for an EXPLOSAFE retrofit such as welding and bolting should be avoided if at all possible. Any tank wall alteration with welding would cause a stress concentration and subsequent decrease in strength which would necessitate stress relieving of the tank and structure. This would cause undue extra expense for a tank car retrofit.

There are procedural problems to be overcome to ease the installation and removal of the structure along with a layer of EXPLOSAFE within a tank car 18.9 m in length and 3.0 m in diameter. The structural components and EXPLOSAFE for example, must be inserted through a 457 mm (18 in) diameter opening. The design must permit the efficient assembly of these components in parallel with the installation of the EXPLOSAFE.

The structure should make allowances for the protruding man-way at the top of the tank, the eduction pipes at the bottom of the tank and also the butt weld ridges within the tank.

The support structure should allow adequate passage of water to the tank wall during the cleaning process. The design must make allowance for removal of a strip of EXPLOSAFE from the bottom of the car to facilitate manual removal of the cleaning process residues. Provision must also be made for a complete removal of the EXPLOSAFE and its support structure for periodic thorough tank cleanings and hydrostatic pressure tests. It is mandatory that a tank is hydrostatically tested every 10 years. More frequent tests are performed if deemed necessary.

3.0 DATA DEFICIENCIES AND PROBLEM AREAS

It became evident during the course of this investigation, that insufficient information was available (or could be generated within the scope of the study) to fully quantify all effects on the installation design. These areas potentially pose extreme problems to the installation as described in the following sections.

3.1 Corrosion Performance

The assessment of the corrosion performance of the EXPLOSAFE mesh within a tank car as outlined in Section 2.5 was based on the results of a literature review and some limited laboratory experiments. The basic mechanisms outlined will be applicable to all aluminum alloys used for the mesh. The severity of the corrosion problem for any alloy will depend on its chemical composition, the type and concentration of impurities found in the tank and the temperature history during operation.

3.1.1 Corrosion Data for Ladings

The estimated corrosion of the reference AA3010 aluminum alloy was based on the performance of AA3003 aluminum alloy in anhydrous ammonia and a comparison of the corrosion behaviour of these alloys in anhydrous methanol. There is no experimental information on the corrosion behaviour of the reference alloy in either lading, although the AA3010 alloy showed improved corrosion performance over AA3003 in an anhydrous methanol environment. Therefore, it is not possible to substantiate the projected corrosion rates for EXPLOSAFE. To be able to do this, experimental results are required for the reference material in the ladings, which can be obtained through the program outlined in Section 8.1.1.

3.1.2 Impurities in the Ladings

An area that is critical to the corrosion behaviour of EXPLOSAFE is the presence of impurities within the tank car. It has been shown that deleterious impurities are introduced into the tank during the cleaning process and modifications to the process to correct this have been proposed. However, it is believed that the ladings also introduce impurities and it is critical to prove or disprove this supposition. If the ladings are contaminating the tank with deleterious impurities then the corrosion processes outlined in Section 2.5 will be present and modifying the cleaning operation will be fruitless. Therefore it is essential that this void in the data be filled.

3.1.3 Lading Temperature

The temperature of the lading within the tank is a very important parameter in the determination of corrosion rates. At present an upper bound of 60°C is proposed. However, all data on which the corrosion rates were based was at 25°C. An in-service time-temperature history of a typical car is required to allow assessment of the most realistic temperature at which to conduct any experimental corrosion tests or base any theoretical assessment. There is no question that any increase in temperature will increase the corrosion rates, but it is not known whether the use of 60°C as the temperature at which to conduct corrosion tests would be realistic. It may be only a very limited time transient.

It would be desirable to have this temperature information prior to the corrosion tests outlined in Appendix D. It would have to be determined by experimental means (using an instrumented car), or supplied by some railway agency. Another possibility is that the data could be determined analytically by the use of some form

of composite weather pattern summation assembled to describe a hypothetical summer. The determination of the car's response to thermal inputs could allow the setting of a realistic mean temperature and determine how frequently the upper bound is approached.

3.2 Dynamic Fluid Slosh

The behaviour of fluid within a tank car in an over-the-rail environment is very difficult to describe. A comprehensive literature search of the subject was conducted and is documented in the reference section of this report (See reference 8-12 and 14-17). No analytical or experimental data were found which enabled a quantification of the sloshing loads which would be imposed in a tank car. In general, the references surveyed presented either too general a treatment, or analysis of specific problems. A brief overview of this material is presented in the following.

References 8,9,10,15,16 and 17 are NASA publications and reflect extensive studies done on the effects of liquid propellant slosh on the stability of rockets. These studies were done in the period 1960 to 1966 as part of the NASA space development program. Reference 16 works from first principles deriving series solutions to lengthy mathematical equations. The examples provided are for spherical and vertical cylindrical containers and no empirical formulas are provided. This reference along with reference 17 by the same author may prove useful in forming a mathematical model of the sloshing in tank cars. Reference 17 provides a computer model for the fluid motion in a tank using a mass-spring-damper analogy. The geometry is again for a vertical cylinder. Reference 11 is a study concerning the effects of fluid slosh in airplane fuel tanks and provides models of vertical cylindrical and spherical tanks using a mechanical analogy. The prime concern, however, is the movement of the

centre of gravity of the fluid and its effect on the stability of the craft. Reference 14 is a basic hydrodynamics text dealing with the motion of non-confined fluids. Some useful information is provided concerning waves and wave motion. Reference 12 is a literature survey of sloshing in moving containers and is dated 1960. This article may be useful as a starting point for future studies.

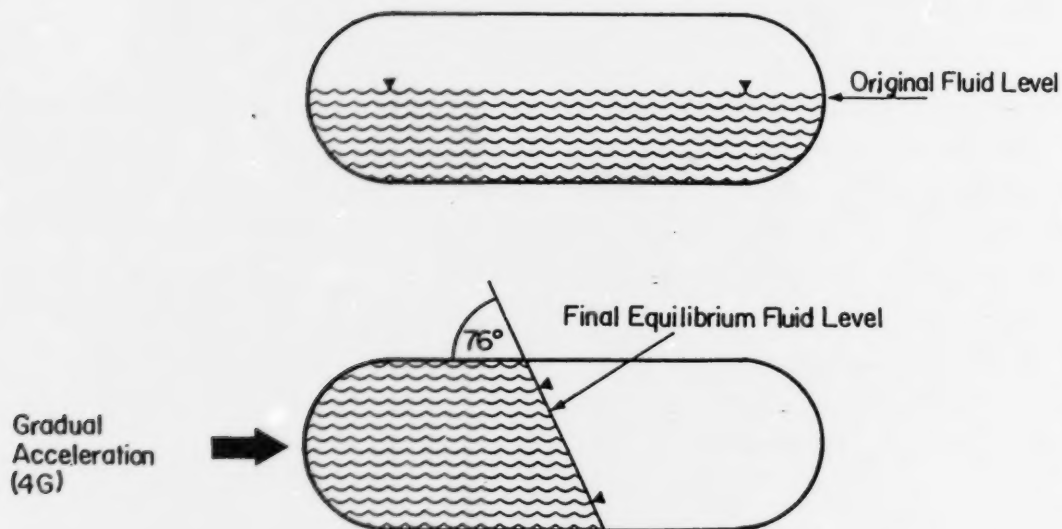
The sloshing phenomenon will be examined below in a preliminary way. The discussion below pertains to a tank 50% full which is the worst design case. The EXPLOSAFE foil and its support structure will undergo fluid dynamic forces when exposed to the tank contents. Forces result from a tank acceleration and subsequent displacement of the contained fluid as would arise during a coupling of cars, braking or during a derailment.

A sustained tank acceleration A_x will have the effect of tilting the fluid free surface through an angle θ at equilibrium where:

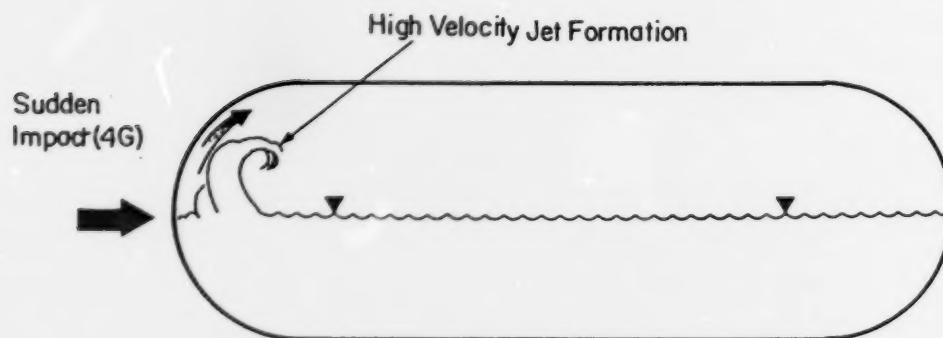
$$\tan \theta = \frac{A_x}{g}$$

At 4g's, θ will be 76 degrees (Figure 2a)

This tilting will result in fluid flow relative to the end caps and along the bottom of the tank.



(a) SUSTAINED ACCELERATION (BRAKING)



(b) ACCELERATION OF SHORT DURATION (IMPACT)

FIGURE 2 - FLUID MOVEMENT DUE TO TANK ACCELERATION

An acceleration of short duration as would occur during impact loading could cause more severe sloshing. Under a 4g longitudinal impact load for example, the fluid within the tank acts instantaneously as a horizontal fluid column of length equal to the length of the tank. Instead of a gradual tilting of the fluid surface, the liquid could climb the tank wall at one end in the form of a high velocity jet (Figure 2b). Such a jet, when it impacts, could cause considerable damage to the EXPLOSAFE or any body attached to the tank wall. Although steady state equations do not strictly apply in this transient case, Bernoulli's equation, converting the instantaneous fluid pressure to velocity, reveals that the jet velocity could be in the order of 60 ft/s under an acceleration of 4g's.

There appear to be two mechanisms causing fluid forces on the EXPLOSAFE. One is flow over the submerged mesh as would occur at the bottom of the tank for example. The fluid inside the mesh will be impeded from taking part in the sloshing by the flow resistance of the mesh. The main tangential flow will then behave as a boundary layer over a very rough wall and will exert a shear force on the mesh. This force will be proportional to the velocity of the fluid adjacent to the mesh and the skin friction coefficient of the EXPLOSAFE. These two parameters are therefore required to more accurately describe the shearing force.

The second mechanism is flow over the dry EXPLOSAFE matrix. This will occur on the end caps and, if there is only a small amount of liquid in the tank, on the bottom wall. As the liquid spreads

over the dry mesh it will penetrate and fill it. The liquid will have components of velocity, V_n and V_t (normal and tangent) to the mesh as shown in Figure 3 below.

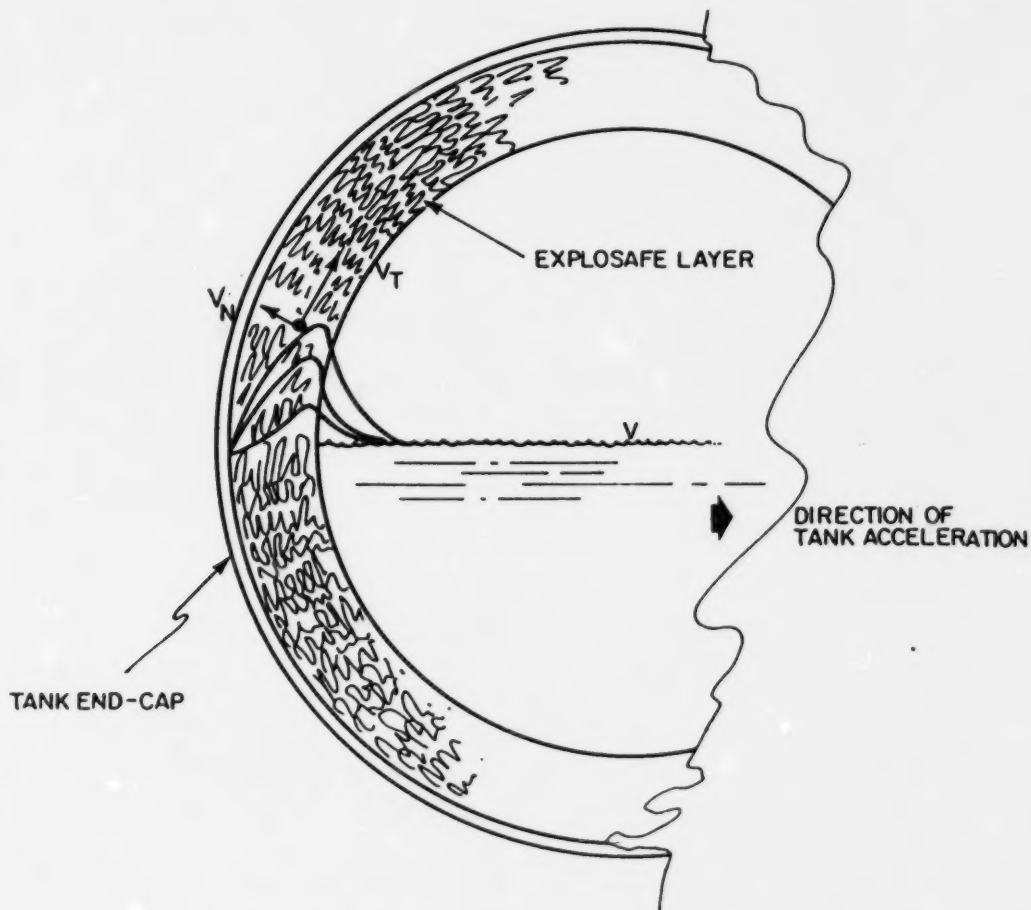


Figure 3 Liquid Penetration of Dry Explosafe Matrix

The normal component gives rise to a compressive force, due to the pressure drop through the mesh. This force is probably not very large. It is a function of the loss coefficient for flow through the mesh, which has already been determined from previous experimental results (2).

The fluid penetrating the mesh will also have tangential momentum due to V_t . Since this velocity component should be largely removed by the mesh, a tangential force equal to the rate of decrease of tangential momentum will be experienced by the mesh:

$$\frac{F_T}{A} = \frac{MV_T}{A}$$

where $\frac{F_T}{A}$ = tangential force per unit area

$\frac{M}{A}$ = mass flow rate per unit area into the mesh

$$= \rho V_N \quad (\rho = \text{density of liquid})$$

It seems likely that the tangential force will be the largest of the two components.

There are also forces transmitted to the support structure itself by virtue of the fluid velocities. Any protruding structural component must supply a force in proportion to its area in order to accelerate the adjacent fluid.

The sloshing phenomenon and the severity of its effect on the EXPLOSAFE installation cannot be completely described presently due to the lack of data. Experimental methods and tests are proposed in Sections 8.1.2 and 8.3.1 which would provide this data.

3.3 Additional Deficiencies

In addition to the two major consideration of sloshing and corrosion, there are some further items which we currently viewed as potential areas of concern.

As mentioned briefly in Section 2.2, the description of the environmental load spectrum and ensuing fatigue analysis would be an important input to a final design. This information, since it is largely specific to a particular railcar and track, would probably have to be measured directly. A procedure is recommended in Section 8.3.2. Only through the results of these tests could an evaluation of the fatigue lives of the various design components be performed.

There have arisen certain concerns that are somewhat beyond the scope of this study but are foreseen as important influences. It is not presently known, for instance, what temperatures would be imparted by a full scale torch impingement fire or a pool fire. As previously mentioned, 1/5 linear scale pool fire tests showed tank temperatures which are below EXPLOSAFE's melting point of 650°C. There is some question however whether a prolonged pool fire on a full scale tank would produce the same tank wall temperatures. A torch fire impinging on the vapour section of the tank could conceivably produce more severe temperatures than a pool fire. The vapor regions of the tank are critical since the heat can only be dissipated through vapor convection and conduction along the tank wall and not through the liquid.

The external insulation currently used on rail tank cars is subjected to test according to U.S. Department of Transportation Specification 179.105-4. The pool fire simulation test specifies a flame temperature of $870^{\circ}\text{C} \pm 38^{\circ}\text{C}$, using hydrocarbon fuel for a duration of 100 minutes. The torch fire simulation test involves a flame temperature of $1200 \pm 38^{\circ}\text{C}$, using hydrocarbon fuel for a duration of 30 minutes. Although these are flame and not tank wall temperatures, since they exceed the melting point of EXPLOSAFE in both test cases, it is possible that the tank wall fitted with EXPLOSAFE would not meet this standard. It should also be stated that EXPLOSAFE works by a different thermal mechanism than does insulation (i.e. by transferring the heat away from the source), and therefore the above test may not be applicable in the strictest sense.

The EXPLOSAFE layer thickness is also an important parameter which is examined in this report. The influence of this parameter on cost is substantial and thus far, no concrete specification could be found on the optimum layer thickness from a thermal perspective.

The latter two inputs should be provided by thermal analyses or tests prior to finalizing an installation design.

4.0 POSTULATION OF OPERATIONAL PROCEDURES

The aim of this section is to speculate as to how the installation of EXPLOSAFE in a tank car may affect the current operational procedures maintained in its operation. Potential modifications are listed and explained below:

(a) On the assumption that the loadings will not introduce sufficient impurities to cause corrosion problems of the type and magnitude specified in Section 2.5, the area which will require changes in the operational procedure will be the cleaning process.

Outside of the changes required to the cleaning process to prevent the entry of deleterious impurities during this operation, the process also requires modifications to the various constituent operations which affect cleaning. The use of EXPLOSAFE will cause the steaming process to be extended by a couple of hours because of the increased surface areas within the tank. In addition, modifications must be made to the drying process so that it can be completed within a reasonable length of time. It is expected that this process would be extended by a couple of hours as well.

The present mopping up operation requires two men and approximately a half-hour including a precautionary inspection of the tank. This procedure would have to be revised to use three men. Two men inside the car would remove and reinstall a strip of EXPLOSAFE from along the entire length of the tank bottom and remove the residual water and crud. The third man outside the tank, would be present for safety reasons and would also clean and dry the removed mesh. This procedure would require two hours and would not include the precautionary inspection of the tank

which cannot be done due to the EXPLOSAFE. However, there would be an inspection of the mesh/tank interface for corrosion. This could be readily done along the bottom of the tank from where the mesh was removed and by removing corrosion test coupons of mesh located at critical points throughout the tank.

(b) It may become necessary in order to contend with corrosion associated with cleaning, that tank cars be restricted to use with one lading only, thus reducing the cleaning frequency.

(c) On-going monitoring of the progress of corrosion during the life of the tank car would likely be necessary to determine at what point the EXPLOSAFE should be replaced. This could be accomplished by inspection of the EXPLOSAFE batts located at strategic points throughout the tank, which are removed during the cleaning process. Corrosion between the support system and the tank wall could also be monitored at this time.

(d) General inspection of the support system should also be performed periodically. The procedure specific to the support structure design presented in Section 5.0 should include the following:

- check corrosion at all expander ring/wall interfaces
- re-torque expander rings
- check ring/wall contact pressure
- check EXPLOSAFE/wall contact pressure
- remove any slack from longitudinal rods
- check rigidity of ring joints

The inspection will ensure that the EXPLOSAFE/wall contact pressure and rigidity of the support structure are maintained. This could again form part of the cleaning procedure.

(e) As a measure to curb the effects of sloshing, it may be advantageous to operate at all times with the tank car fully

laden, in accordance with CTC Regulations. It is anticipated that cars laden approximately 25-75% by volume will exhibit the greatest potential for sloshing damage.

(f) An additional task in the cleaning procedure will be to clean or replace the in-line filter element which will be added to the operator's suction hose to remove particles from the loadings.

(g) It would be advantageous for the cleaning facility to keep frequently replaced parts on stock such as support system components (nuts, expanders), sections of EXPLOSAFE and filter parts.

(h) Another change will be the necessity to remove the EXPLOSAFE whenever a car is to be hydrostatically tested. A tank car is hydrostatically tested every ten years or if there have been repairs to a pressure boundary weld on the tank.

(i) Since any dents found in the pressure vessels cause stress raisers, they are immediately inspected. The presence of EXPLOSAFE would inhibit the internal inspection and repair of such an indentation. The EXPLOSAFE would have to be removed from the damaged area to facilitate repairs.

(j) Items c,d,f,g and h above would likely necessitate the initiation of education seminars for the personnel involved.

5.0 SUPPORT SYSTEM

5.1 Candidate Support Structure Concepts

There were several original design concepts proposed for the support structure. Since the refinement of one design from the proposed concepts, utilizing the design criteria formed part of the design process, it will be described in this section. The proposed concepts were evaluated so that if it is decided at a later date to select an alternate design, these concepts may be reconsidered. The concepts considered and rationale for rejection are given in Appendix C. In most cases, the concepts can be discounted on a structural basis alone.

The reader will note that all methods evaluated for maintaining intimate contact between the EXPLOSAFE and tank wall are mechanical in nature. Adhesives were discounted at an early stage for the following reasons:

- (a) The adhesive would be applied in the precise areas where the corrosion mechanisms are most active and the thin layers of metal which are bonded could be rapidly corroded.
- (b) The adhesive must be able to withstand large forces and very high temperatures.
- (c) The adhesive must remain inert with respect to the ladings, the metals and any impurity found within the ladings.
- (d) Replacement of the EXPLOSAFE would be difficult.

5.2 Proposed Support Structure

The retaining structure design presented has been based upon the criteria outlined in Section 2.7 and is illustrated in Figure 4 (Drawing No. DE1913). The structure is essentially a combination of the features of concepts 5 and 6 presented in Appendix C. The design has been formulated with the knowledge that all of the environmental loads have not yet been quantified. The proposed test program could conceivably reveal that sloshing loads for example, outweigh the inertia considerations. As such, an option to reinforce the EXPLOSAFE is incorporated into the design as a contingency (refer to Option 'B', Figure 4)

A design option is provided for installation of the EXPLOSAFE and supports during tank car manufacture (refer to Option 'A', Figure 4). Both options are essentially variations of the same concept. There are four permutations of the design considered and they are as follows:

1. Retrofit - Expander rings and no protective skin
2. Retrofit (Option 'B') - Expander rings with protective skin
3. Integrated production (Option 'A') - welded rings, no skin
4. Integrated production installation (Option 'A') with (Option 'B') - welded rings with protective skin

It is conceivable that the "integrated production" designs (3. and 4. above) could be implemented in a retrofit. But because of the welds, the tank would require stripping and stress relieving following the weldments which would increase the costs of the installation. Compared with the "retrofit" design utilizing expander rings which impart a radial pressure to the tank, the welded rings would not impart this pressure but the stress concentration due to the discontinuities in the tank wall would be more pronounced.

The designs 1 and 2 involve a support skeleton comprised of circumferentially expanded steel rings of preformed standard 'T' section which are friction fit against the tank wall. The rings are spaced 1.8 m (72 in.) apart longitudinally allowing space for four circumferential 457 mm (18 in.) strips of EXPLOSAFE. Longitudinal rods are passed through the webs of the rings to compress the EXPLOSAFE against the tank wall. The EXPLOSAFE is supported in the 2:1 elliptical end caps by means of standard steel 'T' section preformed into a domed cap which is bolted to the expanded rings at the tank ends.

As previously mentioned, a design option is provided to increase the support and protection of the EXPLOSAFE. This is accomplished by means of a 50% perforated aluminum skin (see Figure 4). The skin sections will be bolted to the support rods with space left between the sections to permit individual removal. The primary function of the skin is to absorb the shear forces exerted by the fluid and to protect the EXPLOSAFE against any transient wave systems. The support structure with the protective skin offers all of the features listed in this section with the possible exception of the ease of tank cleaning. In view of the increased cost, the use of this design contingency would first have to be justified by the findings of the supplemental test program of Section 8.0 (i.e. the discovery of significant sloshing loads). Although the conceptual illustration shows a 114 mm (4.5 in) EXPLOSAFE layer thickness, a support structure was also designed for a 305 mm (12 in) layer. The structure is modified only in the size of its members, not in concept. The extra costs of such a modification are estimated in Section 6.0.

If a tank car is to be equipped with EXPLOSAFE and its supporting structure in parallel with the tank fabrication, the design may be simplified. The erection will be expedited if done prior to affixing one elliptical head since each component need not be

inserted through the 457 mm (18 in.) diameter fill hole. The "T" section expander rings may be replaced by circumferential fins preformed into circular sections which can be welded to the tank wall. The welded rings will exhibit a strength increase over the friction fit rings and any stress raisers caused by the welding process will be removed by the stress relieving process which is currently in practice. The EXPLOSAFE batts may have to be inserted following stress relieving if the temperatures involved exceed the melting point of EXPLOSAFE.

The design exhibits several desirable features which are discussed below:

(a) In the retrofit design, no modifications to the pressure vessel wall would be necessary, although the effect of the ring contact pressure of .34 MPa(g)(50 psig) should be examined in detail. Currently tanks are hydrostatically tested to 2.34 MPa(g)(340 psig) and operate at a maximum pressure of 1.93 MPa(g)(280 psig). Therefore, in a gross sense, the additional pressure exerted by the rings should not be problematic.

(b) The contact pressure of the expander rings is maintained by expander bolts which are located accessibly at the tank bottom. After the proper contact pressure is obtained, the expander bolts are locked with lock nuts so that no loosening occurs. Belleville spring washers are utilized with the expander bolts to exert a constant force even during a tank expansion or deformation. A tank expansion would occur for example, during a pool fire with an internal tank pressure rise. Since the rings are of steel construction, they will expand thermally at the same rate as the tank thereby preserving contact at any temperature.

(c) Each expander ring is preformed in three sections which are bolted together inside the tank. The installation is facilitated

by mounting the expander rings and EXPLOSAFE beginning at one end and progressing longitudinally with the aid of the support rods which are individually threaded into couplings mounted on the rings. The threaded rods permit the easy removal of any section of EXPLOSAFE for inspection or replacement and not only support the EXPLOSAFE radially, but also act as stiffening members for the structure itself.

(d) The total weight added to the tank car is approximately 2500 Kg, 900 Kg of which is contributed by the 114 cm thick EXPLOSAFE layer itself. The weight penalty is therefore not unreasonable and the installation occupies only 0.25% of the total tank volume.

(e) The structure has been designed to support the EXPLOSAFE with sufficient rigidity to prevent excessive movement (hence fretting) of the EXPLOSAFE material. Typically, the design uses a factor of safety of 5.0 based on ultimate strength of the support structure material because of the unknowns (sloshing and derailment forces).

(f) A 457 mm (18 in.) wide strip of EXPLOSAFE is installed longitudinally along the bottom of the tank to be removed to permit mopping up following tank cleaning. With no skin, the support structure retains the EXPLOSAFE over approximately 6% of its area, thus it does not present a significant barrier in cleaning the EXPLOSAFE. The protective skin may considerably inhibit cleaning.

(g) An in-line filter is provided to remove any particles from the lading when it is being extracted from the tank. This debris could conceivably be introduced by the corrosion process or as particles breaking from the EXPLOSAFE mesh. The filter would be installed in the operator eduction hose to facilitate maintenance and prevent exposure to the elements.

(h) The flexibility and contact force features of the expander rings can accommodate any local deformation in the tank wall while still maintaining rigidity. The continuous weld in Option 'A' will provide less allowance since more structural support is provided by this method.

(i) Depending on the EXPLOSAFE layer thickness, the expander rings would either be rolled standard 'T' sections or rolled and welded flat bars forming a 'T' configuration.

(j) Since the man-way assembly protrudes somewhat into the tank, allowance has been made for an opening here in the EXPLOSAFE and support rods. A similar accommodation is made for the suction pipe at the bottom of the tank.

(k) The installation of a friction fit or welded structure inside the tank car would strengthen the pressure vessel and would reduce the possibility of puncture due to external impact.

There are aspects of the design which are viewed as potential problems. These items are brought to light here. Further work would be required with regard to problems noted below, to safely implement any of the proposed design permutations from a technical standpoint alone. Full scale mechanical tests as described in Appendix H would be necessary.

(a) As explained previously, the expander rings exert local radial pressures on the tank wall of approximately 0.34 MPa(g)(50 psig) and will also transmit all baffle loads as axial loads to the pressure vessel. This contact pressure must be maintained in order to withstand the loading imposed by the contents. There remains a question as to whether operation under these conditions would be structurally acceptable.

(b) A problem with the structure installation will be the location of internal tank longitudinal and circumferential butt weld ridges. This problem can be overcome by notching the rings as required to accommodate the wall weld profile. Custom fitting of the rings seems necessary.

(c) Reasonably close tolerances must be maintained during the fabrication and installation of the support system. The expander rings must contact the wall continuously and their circles must lie in planes perpendicular to the tank axes. This is to ensure that there are no gaps between adjacent circumferential EXPLOSAFE strips. As such, the distance between any two expander rings must be constant along the circumference. Longitudinal compression of the EXPLOSAFE will account for this to some extent. Since the length of the tank may vary, allowance should be made during installation, to cut the last EXPLOSAFE strip to fit.

(d) If the sloshing loads are found to be very high, it may be necessary for the support structure to be reinforced. It may also be necessary to use honeycomb material to protect the EXPLOSAFE from the shearing loads. Honeycomb material is expensive but has not been costed in the analysis.

(e) Specific corrosion problem areas have been identified for the proposed design.

Crevice corrosion could be prevalent in the friction fit contact region between the rings and wall. This could reduce the coefficient of friction or locally eliminate contact altogether.

An installation using protective sheeting will likely necessitate a prolonged drying period during the cleaning process. The exposure to hot air could result in extensive pitting corrosion. The protective sheeting could also interfere with the thermal

action of the EXPLOSAFE, since this mechanism is not fully understood.

High galvanic corrosion rates would be present in the contact region between the aluminum skin and steel rods and U-bolts. A progressive deterioration could accelerate fretting and eventually remove the skin.

In general, the corrosion processes between the EXPLOSAFE and the support structure would be similar to that between the EXPLOSAFE and steel tank wall.

6.0 COST EFFECTIVENESS

6.1 Method of Analysis

A cost effectiveness analysis for the installation of EXPLOSAFE within tank cars is an important input in deciding whether the system should be adopted. The present value costs for the EXPLOSAFE installation over a 20 year life cycle are presented here. The analysis assumes that the final engineering design and drawings have been completed and hence these expenses are not reflected in the total cost.

The design evaluated is that described in the previous section and illustrated in Figure 4. The cost figures are summarized in Table 1. The analysis considers the following:

1. Retrofit
2. Retrofit with protective skin
3. Production installation
4. Production installation with protective skin

All four concepts are evaluated for EXPLOSAFE replacement intervals of 1,5,10 and 20 years and for EXPLOSAFE layer thicknesses of 114 and 305 mm.

All figures presented in the table are of a budgetary nature and the assumptions made in the analysis are itemized below:

(a) The installation will be done on a production basis. This will have the effect of reducing installation costs, since material can be purchased in bulk and assembly and fabrication rates will decrease. The fabrication and material costs are based on a production rate of 200 cars per year. Costs are given for an installation by PROCOR with labor rates taken as \$50/man-hour, including overhead.

OP- TION NO.	DESCRIPTION	EXPLOSAFE LAYER THICKNESS (mm)	EXPLOSAFE REPLACE- MENT LIFE (years)	INSTALLATION			ANNUAL MAIN- TENANCE & INSPEC- TION	ANNUAL CLEANING	EXPLOSAFE REPLACEMENT (single)		TOTAL (1983 CAN.)
				MATERIAL	LABOUR	FABRI- CATION			EXPLOSAFE MATERIAL	LABOUR	
1	RETROFIT	114	1	13,000	15,000	19,000	100	1,300	8,900	5,000	279,500
2	"	114	5	13,000	15,000	19,000	300	1,300	8,900	5,000	96,500
3	"	114	10	13,000	15,000	19,000	500	1,300	8,900	5,000	80,500
4	"	114	20	13,000	15,000	19,000	1000	1,300	8,900	5,000	77,500
5	"	305	1	15,500	18,000	23,000	100	1,700	22,000	7,000	548,000
6	"	305	5	15,500	18,000	23,000	300	1,700	22,000	7,000	161,500
7	"	305	10	15,500	18,000	23,000	500	1,700	22,000	7,000	116,000
8	"	305	20	15,500	18,000	23,000	1000	1,700	22,000	7,000	108,500
9	RETROFIT W/SKIN	114	1	17,000	18,000	26,000	100	1,500	8,900	5,000	296,500
10	"	114	5	17,000	18,000	26,000	300	1,500	8,900	5,000	113,000
11	"	114	10	17,000	18,000	26,000	500	1,500	8,900	5,000	97,500
12	"	114	20	17,000	18,000	26,000	1000	1,500	8,900	5,000	94,500
13	"	305	1	20,500	21,000	33,000	100	2,000	22,000	7,000	571,000
14	"	305	5	20,500	21,000	33,000	300	2,000	22,000	7,000	184,500
15	"	305	10	20,500	21,000	33,000	500	2,000	22,000	7,000	139,000
16	"	305	20	20,500	21,000	33,000	1000	2,000	22,000	7,000	131,500
17	Prod. Install.	114	1	11,500	10,000	11,000	100	1,300	8,900	5,000	265,000
18	"	114	5	11,500	10,000	11,000	300	1,300	8,900	5,000	81,500
19	"	114	10	11,500	10,000	11,000	500	1,300	8,900	5,000	66,000
20	"	114	20	11,500	10,000	11,000	1000	1,300	8,900	5,000	63,000
21	"	305	1	14,000	12,000	14,000	100	1,700	22,000	7,000	531,500
22	"	305	5	14,000	12,000	14,000	300	1,700	22,000	7,000	145,000
23	"	305	10	14,000	12,000	14,000	500	1,700	22,000	7,000	99,500
24	"	305	20	14,000	12,000	14,000	1000	1,700	22,000	7,000	92,000
25	PRODUCTION INSTALL. w/skin	114	1	16,000	14,000	19,000	100	1,500	8,900	5,000	271,500
26	"	114	5	16,000	14,000	19,000	300	1,500	8,900	5,000	101,000
27	"	114	10	16,000	14,000	19,000	500	1,500	8,900	5,000	85,500
28	"	114	20	16,000	14,000	19,000	1000	1,500	8,900	5,000	82,500
29	"	305	1	23,000	17,000	23,000	100	2,000	22,000	7,000	559,500
30	"	305	5	23,000	17,000	23,000	300	2,000	22,000	7,000	172,500
31	"	305	10	23,000	17,000	23,000	500	2,000	22,000	7,000	127,500
32	"	305	20	23,000	17,000	23,000	1000	2,000	22,000	7,000	120,000

Table 1 - Life Cycle Cost Analysis

(b) Inflation and interest rates of 10% and 12%, respectively, are assumed.

(c) EXPLOSAFE material cost is assumed to be $\$450/\text{m}^3$ ($\$12.75/\text{ft}^3$). This figure has been supplied by EXPLOSAFE Corporation based upon a 0.076 mm (.003 in) foil thickness and material production for a 305 mm (12 in) layer of EXPLOSAFE. The cost on a volumetric basis may vary somewhat for a 114 mm (4 in) layer thickness. During replacement, it is assumed that the EXPLOSAFE alone is replaced and not the support structure. The replacement costs presented in the table are material and labour costs for a single replacement. The total life cycle replacement cost is dependent upon the replacement interval. The effect of the replacement interval on life cycle cost is shown in Figure 5.

(d) For EXPLOSAFE-equipped cars, maintenance and inspection costs have been combined since the operations would likely be performed concurrently. Maintenance would take into account repair and/or replacement of any damaged EXPLOSAFE section or support system component. Inspection comprises such things as monitoring the EXPLOSAFE corrosion progression as well as checks on the general condition of the support system and the in-line lading eduction hose filter. These annual combined maintenance and inspection costs are assumed to be linearly related to time in service as follows:

\$ 1000	annually	for 20 year	EXPLOSAFE life
\$ 500	annually	for 10 year	EXPLOSAFE life
\$ 300	annually	for 5 year	EXPLOSAFE life
\$ 100	annually	for 1 year	EXPLOSAFE life

(e) Annual cleaning costs assumed are as follows:

114 mm EXPLOSAFE layer	\$1300
305 mm EXPLOSAFE layer	\$1700
114 mm EXPLOSAFE layer with protective skin	\$1500
305 mm EXPLOSAFE layer with protective skin	\$2000

(f) The cost increase for the 305 mm layer is attributed to a larger amount of EXPLOSAFE to be handled and the fabrication and installation of a more rigid support structure. Costs for any intermediate layer thickness may be approximated by interpolating linearly using the above figures (see Figure 6)

(g) The analysis does not take into account the potential lost service time incurred due to extra cleaning required and intermittent replacement of the EXPLOSAFE.

(h) The analysis does not include the possible purchase of spare parts for replacement or capital costs of additional cleaning system equipment which may be required.

6.2 Summary of Results

Results for EXPLOSAFE-equipped cars range from \$63,000 (integrated production installation, 114 mm EXPLOSAFE layer, replacement interval 20 years), to \$571,000 (retrofit installation with protective skin, 305 mm EXPLOSAFE layer with annual replacement of EXPLOSAFE).

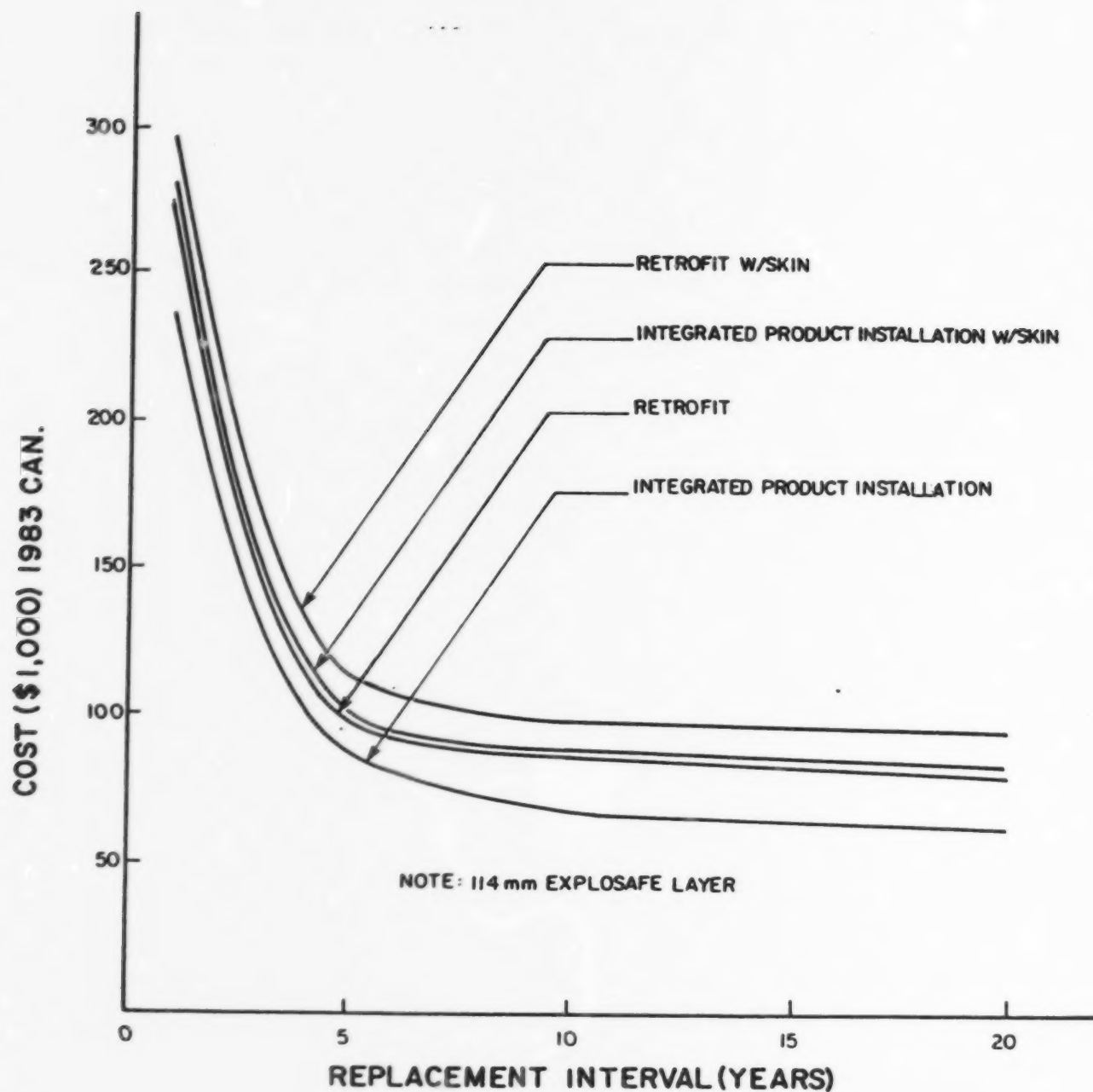


Figure 5 LIFE CYCLE COST vs EXPLOSAFE REPLACEMENT INTERVAL

It is perhaps worthy of mention that the present method of tank car thermal protection (exterior thermal insulation), has a 20 year life cycle cost on a tank car of approximately \$23,500. This figure is based upon a \$10,000 combined material, labour and fabrication cost as provided by PROCOR. The insulation, in accordance with PROCOR's experience, is essentially maintenance free.

Figure 5 demonstrates the influence of EXPLOSAFE replacement interval on cost. The effect is of course more pronounced for a 305 mm layer of EXPLOSAFE. It is apparent from this result that if corrosion for example, dictates a high frequency of EXPLOSAFE replacement, the installation would have a very large economic penalty as compared to an insulated car.

Figure 6 illustrates a rise in life cycle costs with EXPLOSAFE layer thickness. The slope of the curve will increase with more frequent EXPLOSAFE replacement. The results are plotted for a five year replacement interval.

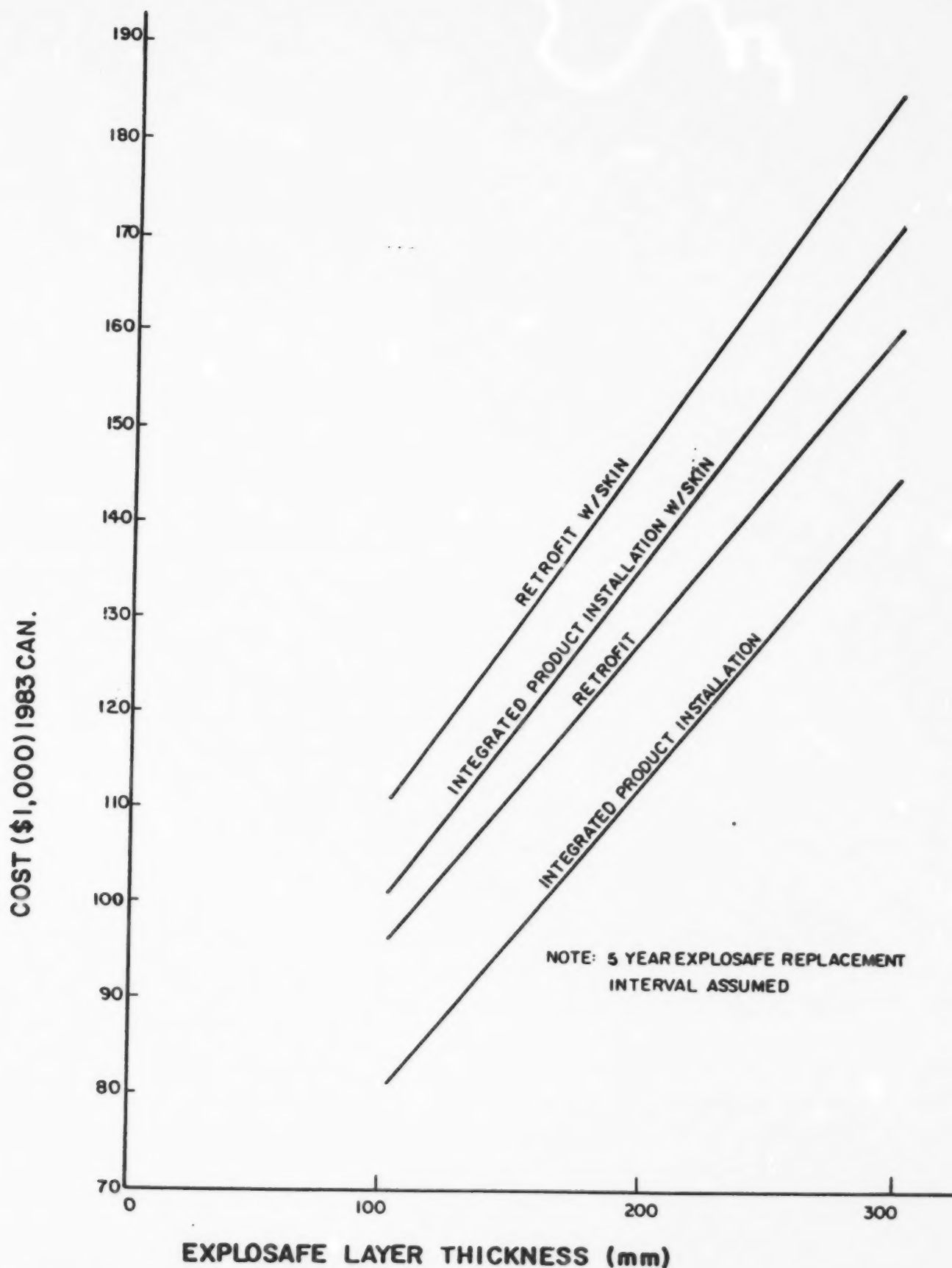


Figure 6 LIFE CYCLE COST vs EXPLOSAFE LAYER THICKNESS

7.0 DISCUSSION OF RESULTS

A review and interpretation of the study results will be presented in the three categories investigated; mechanical, corrosion/cleaning and economic. These topics and their interrelation are discussed in the following sections.

7.1 Mechanical

The acquisition and evaluation of information pertaining to EXPLOSAFE material, rail tank cars, in-service conditions etc., as described in the previous sections, have led to a definition of the requirements for an installation design. Some interpretations of the results of this evaluation process are discussed here.

The number of tank cars operating in Canada is substantial (See Section 2.1), especially if foreign (U.S) owned cars are included. A full fleet retrofit or integrated production installation and subsequent maintenance program would be a considerable undertaking.

A review of tank car environmental conditions brought to light some areas of data deficiency which are explained in Section 3.0. The lack of applicable fatigue (vibrational load spectrum) and fluid sloshing data was identified. In addition, a potential difficulty may exist due to excessively high temperatures occurring during torch impingement or flame engulfment fires. Data in this regard is also unavailable.

Based on the 1/5 linear scale flame engulfment tests, however, the temperature would not be excessively high so as to melt the EXPLOSAFE. Also, based on a previous fatigue study performed on EXPLOSAFE installed in an aircraft tank, fatigue should not be a

problem for the EXPLOSAFE material itself. Further testing in both areas would be required to ascertain their effects on the specific installation.

An installation design has been developed to sufficient detail to permit budgetary costing and mechanical and corrosion analyses. The design considers four options, one of which can be selected when current data deficiencies are filled. The protective skin, for example, may or may not be necessary depending on further input from the sloshing studies. The rings could be held by friction or welds, depending on whether the installation is a retrofit or on a production basis. The design does comply with the known requirements of maintaining contact pressure, adequate support of the EXPLOSAFE under known impact and thermal environments, and tank distortions which occur.

The design presented is that illustrated in Figure 4 and described in Section 5.0.

A noteworthy point is that even if further tests were to show that the design is feasible from a technical stand point, there remains the problem of obtaining the approval of certain governing bodies. Any EXPLOSAFE installation design would involve subjecting a tank car, which is essentially a pressure vessel, to loads in excess of the present normal operating loads. As such, the design would first require the approval of the Railway Transport Committee of the Canadian Transportation Commission and the American Association of Railroads.

7.2 Corrosion/Cleaning

The corrosion and cleaning study results are interrelated. The commonality being the impurities which can be found within a tank car. It will be the ability to control the ingress of these impurities which may dictate whether EXPLOSAFE can successfully be used.

As stated before, there may be some question as to whether the corrosion rate estimates are correct because of the lack of experimental verification for the reference aluminum alloy, but there is no question as to the stimulative effect of the impurities identified in Appendix A on the various corrosion mechanisms. The pure ladings represent relatively benign environments where corrosion mechanisms such as galvanic corrosion between the steel and the aluminum would be non-existent, with the corrosion rate of the aluminum equivalent to being immersed alone in the lading. However, with the introduction of impurities such as water and/or alkali metal chlorides, the situation changes. The corrosion rate moves from a few $\mu\text{m-a}^{-1}$ at the contact to $50\mu\text{m-a}^{-1}$.

The corrosion mechanisms associated with the cleaning process (general attack on the aluminum from concentrated salt liquors and the crevice corrosion of the steel tank), would be prevented from occurring by the lack of impurities.

The difficulty in dealing with the impurities stems from controlling the ingress into the tank. The cleaning process can be modified not only to make it function with an EXPLOSAFE equipped car but also to prevent contaminating it. The most difficult aspect is to determine how much of the impurities found within a tank car come in with the ladings. If the amount is substantial there are serious problems.

If the estimated corrosion rates are assumed to be correct, the approach taken will depend on the concentration of the impurities within the lading. Assuming that the concentrations are high enough to cause the projected corrosions rates upon entry into the car, these rates will either have to be accepted or EXPLOSAFE not used. If the concentrations in the ladings are low and the problem is the accumulating concentration in the tank with use, it

might be possible to control the levels by periodic cleaning. Unfortunately, the present cleaning process cannot effectively remove impurities and it would have to be modified incorporating the use of complexing agents. The cost to clean a tank would then be substantially higher than the present rates. Additive to the incremental increase in cost would be the probable requirement for an increased frequency of cleaning which would be dictated by the projected rate of impurity build up within the car.

Assuming the presence of impurities, the failure of the EXPLOSAFE system by corrosion can take place in two readily identifiable modes; either by destruction of the aluminum mesh by galvanic corrosion such that intimate steel/aluminum contact cannot be assured or by crevice corrosion of the steel tank. A third mechanism has been suggested; that of pitting of the aluminum mesh by concentrated salt liquors, but there does not exist experimental or theoretical evidence to verify this mechanism.

The galvanic corrosion rate is predicted be approximately $50 \mu\text{m-a}^{-1}$. At that rate, it would take roughly 9 months to destroy a $75 \mu\text{m}$ section of foil (attack all sides). The galvanic coupling occurs not only at the steel/aluminum contact but a distance approximately 2 mm outward. Across that distance, the galvanic corrosion rate drops from a peak at the interface to only a few $\mu\text{m-a}^{-1}$ at the 2 mm point. Assuming that the corrosion rate of $50 \mu\text{m-a}^{-1}$ applies across the full extent of the galvanic coupling distance, it would take only nine months to lose 2 mm of EXPLOSAFE material. This assumption may not be that pessimistic as the additive effect of fretting is not included which would remove the passivating layer from the aluminum in contact with the steel. The EXPLOSAFE replacement life due to corrosion can now be defined if it is assumed that replacement occurs when EXPLOSAFE/wall contact is lost.

If the aluminum mesh were 114 mm thick and positioned by either the retrofit or integrated production design (no aluminum skin), it would take approximately 14 months to loosen the EXPLOSAFE (corrosion at tank and rod), at 5% compression. This assumes that the foil will be capable of springing back the full 5%. If such is not the case, corrosion failure will have occurred earlier. When 305 mm foil is used at 5% compression, the projected lifetime is 3 years. The presence of a protective aluminum skin will not alter the corrosion failure times since the steel rods are still in direct contact with the EXPLOSAFE.

The second mode of failure is the initiation and continuation of crevice corrosion in the tank car wall with subsequent cleanings. The major question to be answered is the extent that these crevices can be allowed to penetrate the wall. If there is no corrosion and wear allowance for these tanks, any reduction in wall thickness is not acceptable and failure could occur with the first cleaning. If there is an allowance, the longevity of the tank will be dictated by the time to reach a minimum acceptable wall thickness. The consequence of this corrosion type is high, namely the cost of a tank car. If the figures in Appendix A are examined, it is obvious that it would be very difficult to effect repairs economically.

In light of the problems documented in this section with corrosion specific to aluminum, it may be worthwhile to pursue the use of materials for EXPLOSAFE which are more corrosion resistant. Materials such as mild steel, stainless steel or an improved aluminum alloy, if compatible with foil production methods and exhibiting the desired thermal properties, may be more suitable in this application.

7.3 Economic

The cost effectiveness analysis presented in Section 6.0 consists of a 20 year life cycle evaluation of several variations of one EXPLOSAFE-equipped car concept. The general results are that the cost of the EXPLOSAFE installation varies from \$63,000 to \$571,000 per car as dictated by the particular design variation chosen. These values seem excessive in view of the fact that the life cycle cost over the same period for exterior tank insulation is \$23,500. The actual cost of the EXPLOSAFE design will depend largely upon the actual corrosion rates which dictate the EXPLOSAFE replacement interval and layer thickness as prescribed by a thermal model (See Figures 5 and 6).

7.4 Further Studies

The study thus far has brought to light certain aspects concerning an EXPLOSAFE installation within a tank car which must be interpreted as problematic and may perhaps be prohibitive.

If it is decided to reach an ultimate implementation decision based on further technical and economic evidence, the proposed test programs outlined in Section 8.0 may be carried out in part or in full.

The supplemental test results may be beneficial in their own right since they may be applied in related areas. The planned tests and analyses would serve to fill the voids in the technical data and also determine the total developmental and implementation costs of disseminating EXPLOSAFE-equipped cars throughout Canada.

(Δ - GO/NO-GO DECISION POINTS)

* WNRE - Whiteshell Nuclear Research Establishment

ACTIVITY

CORROSION

STUDIES

- Carleton University

- National Research Council

- Ottawa Diving Services

- Explosafe

SLOSHING

STUDIES

SUPPLEMENTAL TEST PROGRAM

REDEFINITION

OF SUPPORT
SYSTEM

FULL SCALE

IMPACT TEST

FULL SCALE

ROAD TEST

PRODUCTION

DESIGN OF
SUPPORT SYSTEM

0

4

6

10

34

36

(MONTHS)

FIGURE 7 SCHEDULE OF ACTIVITIES FOR FUTURE TEST PROGRAMS & ANALYSES

ESTIMATED
COST
(\$ x 1000)

72.3

19

58

143.5

449.3

47.5

ANTICIPATED
ASSIGNMENT OF
TASKS TO *

WNRE

ME, CU

DE, CU

NRC; ME, PROCOR, OI

DE, WNRE, PROCOR, EXP,
DOM. PET., OR OTHER
COMPANIES

ME, PROCOR

789.60

= TOTAL

8.0 FUTURE TEST PROGRAMS & ANALYSES

Figure 7 presents the activity flow chart for the future test programs and analyses. It shows the basic layout of the program required to conduct various tests and analyses including their respective schedules and cost estimates. It also indicates GO/NO-GO decision points at various stages during the program. The total anticipated program cost is \$789,600.

A number of design concepts of the EXPLOSAFE systems have been proposed. Two problem areas which have to be considered prior to the undertaking of any full scale tests would be the verification of the sloshing loads within the car and the substantiation of the corrosion rates estimated in Section 2.5

In view of the above, the supplemental tests are proposed to clarify the uncertainties in these areas. If it is found that the results of either of these tests are so negative as to preclude further development of the EXPLOSAFE installation design, then further work on this program would be terminated. In the case of the sloshing program, it would be the inability to practically design around the problem. In the corrosion performance, it would be unacceptably high corrosion rates which could not be effectively controlled.

Although the costs of the supplemental programs are high, the costs would be justified if their results are negative and preclude the far more costly full scale mechanical test program. The supplemental program may also be beneficial in other applications.

The results of the supplemental program, if positive, would be utilized to redefine the support system for the full scale test programs.

The full scale mechanical test programs will be comprised of impact and long term (approximately two year) road tests. If the results at the end of each test are favourable, the design of the support system will be finalized to the production quality for equipping the existing fleet of tank cars with EXPLOSAFE.

8.1 Supplemental Test Programs

8.1.1 Corrosion Laboratory Tests

The initial assessment of the corrosion performance of EXPLOSAFE mesh, for tank car applications, demonstrated that insufficient data exists on the corrosion of aluminum alloys in A.A. and LPG environments to enable long term predictions to be made with a reasonable degree of certainty. The effect of impurities present in the ladings or introduced during the cleaning and drying operation, must be understood much better and in particular their effect under conditions of galvanic coupling of the aluminum to steel. A laboratory testing program has been outlined (Appendix D) which would provide sufficient data to clarify this situation and facilitate the prediction of corrosion performance of EXPLOSAFE mesh under real transport conditions.

8.1.2 Sloshing Analysis and Tests

The general objective of these analyses and tests is to quantify the fluid action within a tank car and to determine its effect on an EXPLOSAFE installation. A program to realize this objective is described in Appendix E.

The first step is a first order analytical model of the sloshing mechanism within the tank neglecting the presence of EXPLOSAFE. The model will predict the fluid velocities which would be imposed by the tank car operational environment. Since the EXPLOSAFE would have a damping influence upon the fluid, the

model should yield somewhat higher than actual velocities and lead to a conservative analysis. The model should also predict the tank fluid level producing the most damaging fluid velocities.

These velocities would then be used as inputs in formulating an experimental test program to determine the magnitudes of the fluid dynamic forces which they would exert upon the EXPLOSAFE and its support structure. These experiments would be primarily aimed at obtaining the coefficient of fluid drag of submerged EXPLOSAFE as well as a measurement of the effects of liquid penetration into the dry mesh.

The results of this study will lead to a better understanding of the forces imposed upon the EXPLOSAFE and support structure and will therefore lead to the selection of the appropriate design concept.

8.2 Redefinition of Support System

One variation of the EXPLOSAFE liner and support system design will be selected out of the four proposed concept variations. The design will be modified and redefined as dictated by the supplemental results of the sloshing and corrosion studies. A detailed description of the activities required appears in Appendix F.

8.3 Full Scale Test Programs

A full scale railway tank car will be retrofitted with EXPLOSAFE and a support structure according to the redefined concept. The car will be subjected to various mechanical and corrosion tests. The scope and sequence of these tests is outlined in the following sections. It may be of particular interest to perform a full scale fire engulfment test on the EXPLOSAFE-equipped car

following the long term mechanical test. Although a fire test forms no part of this report, such an exercise would attest to the functional capability of the EXPLOSAFE system after being subjected to an over-the-rail environment.

8.3.1 Impact Tests

This test program will be carried out to investigate the effect of a sudden deceleration of the tank car. The test car, for the impact test, will be filled with water to its 50% capacity or as determined by the sloshing studies. This level of fluid will be chosen to simulate the worst conditions for sloshing. The total weight of water added during the impact test will be kept below the maximum allowable payload of the tank car. Water will be used as the fluid due to safety and cost considerations. A detailed description of this test program is given in Appendix G.

8.3.2 Road Tests

For the road tests, the fluids will be liquid propane gas and/or anhydrous ammonia. The use of two different liquids will give a fair indication of the corrosion characteristics and the structural integrity of the support system under different environmental conditions. The details are given in Appendix H.

a. Mechanical Test Program

This test will determine the fatigue failure criteria for the various components of the support system over the life of the car by determining the load spectrum and identifying critically stressed components. In order to proceed with this test, the support system and the specific areas of the tank car such as end caps, support system pressure rings etc., will be instrumented with sensors and pick-up devices. Data will be recorded on an on-board monitoring and data acquisition system.

A detailed description of the test program is given Appendix H and designated as task "A".

b. Corrosion and Cleaning Program

The corrosion and cleaning test-programs will run concurrently with the mechanical test program. The EXPLOSAFE equipped tank car will be cleaned in accordance with the requirements of the mechanical test schedule of every three months during the first year and every six months during the second year. The corrosion tests are quite straight forward involving the removal and examination of test coupons at regular intervals. The cleaning program is more complex as it involves some additional equipment development, some cleaning hardware specification and development, and as well the program will involve a large degree of trial and error in the drying phase.

A detailed outline of both test series complete with a combined activity flowchart and estimated program cost are given in Appendix H and designated as task "B".

8.4 Production Design

Based on the results of the various investigations, analyses, tests and studies covered in the activities listed earlier in the report, a production design will be finalized. The final design will be presented which will be based on the assumption that a retrofit is required of the existing fleet of tank cars and as part of the production for new cars. Details are given in Appendix I.

9.0 CONCLUSIONS

- 1) An EXPLOSAFE installation with several options has been developed which would meet the requirements of the known mechanical loads. The most suitable option would be selected following the results of the proposed supplemental sloshing studies, full scale tests, and input from thermal model studies. The thermal model studies could determine the optimum layer thickness of EXPLOSAFE, or perhaps even select a material which is not as corrosive as the aluminum EXPLOSAFE.
- 2) Preliminary estimates indicate that the rate of corrosion of the aluminum EXPLOSAFE would be high in the environment of the rail tank car. On the assumption that the estimated corrosion rates are correct, and considering the relatively large fleet of rail tank cars in Canada, the life cycle and further developmental costs of the full scale test programs to implement EXPLOSAFE material in rail tank cars would be very high. Because of the technical problems identified, the proposed three-year development could very well require additional unanticipated efforts, thereby extending the plan and augmenting the costs.
- 3) A tank car with EXPLOSAFE installed would affect the operational procedures at least in the following ways:
 - cleaning - tank car cleaning would become more time consuming, possibly requiring changes in procedures.
 - inspections - inspection of the interior tank walls normally done during the cleaning process would be inhibited by the EXPLOSAFE, possibly leading to fewer inspections.

filtering - an in-line filter would be necessary to trap any debris originating in the tank while emptying the tank at a storage station.

lading - in order to minimize the rate of corrosion of the EXPLOSAFE, it may be necessary to operate a tank car with one lading only.

4) Irrespective of the thermal consideration, the proposed supplemental tests (corrosion and sloshing) could be implemented as their results may be useful in applications beyond the currently envisaged EXPLOSAFE installation program. Some examples are:

- verification of the various postulated corrosion processes would be applicable to the use of all aluminum alloys within the reference loadings.
- characterization of the loadings and their impurities would have applications in the definition of the corrosion processes which other materials would undergo in these loadings.
- the understanding of the fluid mechanisms obtained from the sloshing studies could be applied to determine the forces on other structures within a tank car.

5) After consideration of the difficulties and costs associated with the installation of aluminum EXPLOSAFE mesh in rail tank cars, and in consideration of the apparent experience with external insulation, it is the opinion of Davis Engineering Limited that the concept of aluminum EXPLOSAFE in rail tank cars should not be pursued.

This is not to say that novel and potentially improved methods of protecting tank cars in a hostile environment (i.e. pool or torch fire) should not be pursued.

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APPENDIX A

CORROSION PERFORMANCE OF TANK CARS

THE CORROSION PERFORMANCE OF EXPLOSAFE
EQUIPPED TANK CARS

SUMMATION

1. The extent of corrosion on EXPLOSAFE foil, when used for tank car applications, is likely to be very dependent on the presence of impurities in the ladings.
2. In high purity anhydrous ammonia at ambient temperatures the general corrosion rate is likely to be less than a few $\mu\text{m-a}^{-1}$ (fraction of mil per year). Galvanic contact between the aluminum-mesh and the steel surface of the tank car will not change this rate.
3. The presence of small quantities of water (as little as 0.2 wt%) in anhydrous ammonia can result in a significant increase in the corrosion rate of aluminum in galvanic contact with steel. Metal loss rates of $50 \mu\text{m-a}^{-1}$ year can be expected, and on the very thin EXPLOSAFE mesh (cross-section $75 \mu\text{m}$), penetration would be rapid.
4. The presence of other contaminants, such as alkali metal chlorides, are also likely to increase the corrosion rate of aluminum in galvanic contact with steel. The occurrence, simultaneously, of water and chloride in the anhydrous ammonia, is likely to have an additive effect, the corrosion rate being greater than in the presence of water or chloride only.

5. The presence of contaminants is also likely to increase the rate of fretting corrosion of the EXPLOSAFE mesh in contact with the steel tank car surface.
6. In general, it would be expected that the corrosion behaviour of EXPLOSAFE in LPG would be similar to that in anhydrous ammonia if contaminants, such as water and chlorides, are present.
7. Cleaning and drying of the tank cars between loadings could result in accelerated corrosion of both the aluminum mesh and the steel tank car surfaces. This is because of the following facts:
 - (a) Elevated temperatures are used in these operations.
 - (b) Air drying ensures the presence of excess oxygen at wet metal surfaces.
 - (c) Aggressive contaminants such as chlorides and sulphates are present in the cleaning water.
 - (d) Concentration of these contaminants by evaporation to form very concentrated salt liquors on metal surfaces.
 - (e) The convoluted structure of EXPLOSAFE restricts mass-transport during the evaporation stage, thereby prolonging final dry-out of these aggressive liquors.

THE CORROSION PERFORMANCE OF EXPLOSAFE

EQUIPPED TANK CARS

Three distinct phases of tank car operation were identified which warrant a detailed corrosion assessment. These are:

- (1) During the transport of Anhydrous Ammonia (A.A.).
- (2) During the transport of Liquid Propane Gas (LPG).
- (3) During the cleaning and drying between loadings.

Each of these will be discussed in relation to the likelihood that corrosion will occur on the aluminum EXPLOSAFE mesh and/or the ferritic steel of the tank car, and in particular, the probable corrosion mechanisms will be identified and an estimation made of the severity of attack in each phase.

Anhydrous Ammonia (A.A.)

General corrosion rates of aluminum (3003) and low alloy steels are less than $25 \mu\text{m-a}^{-1}$ (1.0 mpy) in anhydrous ammonia at ambient temperatures [1,2]. These rates are not measurably affected by the presence of contaminants such as water or air (oxygen and nitrogen). However, when aluminum is in contact with ferritic steels, the galvanic corrosion rate on aluminum is then very dependent on the presence of impurities, in particular water.

The galvanic series in anhydrous ammonia is similar to that found in aqueous environments, e.g., sea-water, which means that aluminum is active with respect to ferrous alloys and behaves as a sacrificial anode when in galvanic contact. In A.A. there is

no significant effect of galvanic coupling and corrosion rates are very similar to those in the uncoupled condition. The addition of 0.2 wt.% of water results in a large increase in the galvanic corrosion rate of aluminum and, for example, a rate of $375 \mu\text{m}\cdot\text{a}^{-1}$ (15 mpy) was measured on alloy 3003 for an area ratio of steel to aluminum of 15:1 [2]. Decreasing the area ratio results in a decrease of rate, such that at a ratio of 1:1 it is $75 \mu\text{m}\cdot\text{a}^{-1}$ (3 mpy) and at 1:15 about $25 \mu\text{m}\cdot\text{a}^{-1}$ (1 mpy). The corrosion rate of the low alloy steel (cathode) remains unchanged, but its resistance to stress corrosion cracking is increased by cathodic protection. The presence of air/oxygen has no effect on the galvanic corrosion rate which suggests that the acceleration is the result of enhancement of the hydrogen evolution kinetics (cathodic partial corrosion reaction) on the steel surface, due to the presence of water in the A.A..

If the policy is retained of deliberately adding small quantities of water to A.A. to suppress stress corrosion cracking of the quenched and tempered steel tanks, then, based on the above rates, penetration of the thin EXPLOSAFE foil (75 μm) could be rapid. For the proposed use of EXPLOSAFE in tank cars it is probable that a different 3000 series aluminum alloy would be chosen and this could result in much lower galvanic corrosion rates than those measured on 3003.

The most likely alloy to be used for tank car applications is AA3010 [3,4]. No corrosion data could be found for this alloy in A.A., however a comparison of its corrosion behaviour with that of 3003 in anhydrous methanol, containing 0.1 wt.% NaCl, was reported [3]. This showed that 3003 corroded very rapidly in this environment ($3250 \mu\text{m}\cdot\text{a}^{-1}$) whereas 3010 corroded at a much lower rate ($2.5 \mu\text{m}\cdot\text{a}^{-1}$). Galvanic coupling to an equal area of mild steel caused a significant increase on both alloys, however

the difference in rates was much less under these conditions ($1750 \mu\text{m}\cdot\text{a}^{-1}$ for 3010, $8000 \mu\text{m}\cdot\text{a}^{-1}$ for 3003). Severe pitting corrosion was observed on both alloys when coupled to mild steel and crevice corrosion was also noted on the 3003 alloy. The implication of these results for the corrosion performance of 3010 in A.A. is not clear but it would appear that galvanic coupling to ferrous materials causes a significant enhancement in the corrosion rate of aluminum alloys in these non-aqueous environments, particularly in the presence of impurities (H_2O , Cl^-).

It was stated previously that a small ratio for the area of steel to aluminum would favour a low galvanic corrosion rate on aluminum. Hence, maximizing the area of the EXPLOSAFE mesh (e.g., by increasing the thickness of the installation) may reduce the overall corrosion rate to an acceptable value. However, there is likely to be a limit, such that further increase of area has no effect on the corrosion rate. The reason for this is related to the very low specific conductivity of A.A. which would lead to a large resistance polarization between the steel and successive layers of EXPLOSAFE foil. The net result of this polarization would be that foils greater than a certain distance from the steel surface would not influence the galvanic corrosion behaviour of the couple. This distance could be very small (a few millimetres) due to the high specific resistance of the A.A. The maximum rate of galvanic corrosion would be expected to occur close to the points of contact between the aluminum and steel, and this would be highly undesirable in the present application.

Fretting corrosion of aluminum (galvanically coupled to steel) could be significant in an A.A. environment contaminated with low levels of water. Fretting corrosion occurs by periodic rupture of the passive layer followed by rapid dissolution of the underlying metal before passivity is regained by film growth processes (repassivation). Factors which hinder repassivation

and enhance dissolution of the bared metal surface will increase the rate of fretting corrosion. The low availability of passivating species in A.A. (e.g. OH) will mean that repassivation is slow and galvanic coupling will increase the anodic dissolution rate of the bared surface.

The effects of contaminants such as alkali metal chlorides on corrosion processes in A.A. are not known, however, if the effects are similar to those in anhydrous methanol, discussed previously, pitting and crevice corrosion may also have to be considered (assuming these contaminants are present). These impurities would also have a detrimental effect on fretting corrosion by delaying repassivation and enhancing dissolution.

Liquid Propane Gas (LPG)

To date, no data have been found for the corrosion of aluminum alloys in liquid hydrocarbon environments. However, it is possible to speculate on this, based upon the behaviour observed in other non-aqueous environments. It would appear that significant corrosion can occur in these environments if small concentrations of impurities are present which can stimulate the kinetics of the partial cathodic (e.g., water) and anodic (e.g., chlorides) reactions. Galvanic coupling to an iron based alloy, under these conditions, causes a marked increase in the rate of corrosion on aluminum alloys.

Cleaning and Drying of Tank Cars

It was reported [5] that the present cleaning operation involves a steam/water wash at 160-170°C for times between 6-8 h. The time for this wash may have to be extended if EXPLOSAFE were installed in tank cars, since the surface area to be cleaned would be much greater, and considerably more convoluted, than that of the plain steel tank car. Similarly, the drying

operation, which uses a flow of air, at a controlled relative humidity (R.H.), is likely to require longer than at present (2-4 h). Although the total time spent in cleaning and drying is insignificant, compared with the timescale of the transport phase, it is considered that the elevated temperature conditions, the free aeration of hot surfaces and the galvanic couple between EXPLOSAFE and the steel tank could result in accelerated corrosion rates and extensive corrosion damage on this short timescale.

During drying of the tank car, evaporation of the cleaning water would concentrate salt impurities, present in the water, to form concentrated salt liquors on the EXPLOSAFE and tank car surfaces. These salts (chlorides, sulphates, carbonates, etc.) could originate either from the cleaning water itself (town mains water used) or by leaching of salts deposited in previous cleaning operations. It is considered that these hot concentrated salt liquors could cause rapid corrosion of both the aluminum and steel, the extent of corrosion depending on the time for which they persist before complete dry-out takes place. Due to the restricted mass-transport offered by the EXPLOSAFE structure, evaporation to dryness of solutions inside the mesh is likely to take much longer, increasing the likelihood of corrosion damage compared with the situation at a free surface.

Proposed Experimental Work

Accurate corrosion rate data are required on AA3010 (in galvanic contact with TC 128 steel) in both A.A. and LPG environments, with and without the addition of impurities (e.g., H_2O and Cl^-). The present program was limited and did not allow sufficient time or resources to carry out these studies. However, short-term experiments were carried out to see if accelerated corrosion did occur during a simulated cleaning and drying operation.

EXPERIMENTAL

Objective

In order to perform these experiments, EXPLOSAFE mesh was sandwiched between plates of typical tank car steel in order to achieve galvanic contact. These compacts were saturated with simulated cleaning water, heated to 150°C in an autoclave, then, after a pre-determined time, the water was evaporated off in a stream of dry air passing through the autoclave. Detailed metallographic examination of the foil and steel surfaces were carried out to assess corrosion damage.

Test Procedure

After cleaning and drying, the EXPLOSAFE mesh was compressed between the steel plates using a bolted arrangement. The thickness of the mesh was about 50 mm. Two samples were placed in the autoclave, the sample at the bottom comprised of plates A1 and A2, the top sample plates B1 and B2.

Approximately 400 mL of test solution were placed in the autoclave resulting in complete immersion of sample A1, A2 but only partial immersion of sample B1, B2.

After sealing, the autoclave was heated to 150°C (cycling between 140°C and 160°C). This temperature was maintained for about 22 hours. During this time the pressure in the autoclave increased from about 450 kPa(g)(65.3 psig) to 800 kPa(g)(116 psig) with no increase in temperature.

After 22 hours the pressure was slowly released and air circulated through the autoclave to dry the samples. The time from the initial release of pressure to termination of test was 113 minutes. Air was circulated for a period of about 97

minutes. During this time there were large changes in temperature; however, the average was 119°C.

After the test was completed, samples were removed, disassembled, microscopically examined, photographed and reweighed.

Results and Discussions

The weight change results for the steel plates are shown in Table A.1. A weight change measurement was not made on the aluminum mesh as it would be difficult to relate this to a meaningful average metal loss rate due to uncertainties in estimating the area of the mesh. Metallographic examination was relied upon to assess the extent of corrosion on the aluminum foils in the mesh.

It can be seen from Table A.1 that a positive weight change was observed on the steel plates totally immersed (A1 and A2) and a negative change on those that were partially immersed (B1 and B2). Visual examination of the plates showed that extensive corrosion had taken place on all of them. It is considered that the weight changes do not reflect the true metal loss, and determination of this would require treatment with an inhibited acid to remove the adherent corrosion products. However, time did not permit this procedure to be carried out. Also, visual examination of the plates showed that corrosion was non-uniform, but occurred predominantly on those surfaces in contact with the aluminum mesh (see Figures 1(a) and (b)). Corrosion was localized at the areas where the aluminum foil was in contact with the steel surface and it can be seen (Figure 1(a)) that the corrosion product was a different colour (black) in these areas. It is proposed that rapid crevice corrosion was taking place in these areas with the corrosion being due to an acidic mechanism involving the formation of magnetite and the liberation of hydrogen. The liberated hydrogen would account for the

significant increase in pressure in the autoclave during the experiment. The un-creviced areas appeared to be passivated with a thin film of hydrated ferric oxide.

On the partially immersed specimen very pronounced corrosion occurred around the water/steam interface, and attack was equally severe on both surfaces of the plates (Figures 2(a) and (b)). The corrosion product appeared similar to that formed on the immersed specimen in those areas where there was contact between aluminum foil and steel surface.

A careful examination of the aluminum foils using a stereo microscope showed no evidence of corrosion attack. This was true for foils in direct contact with the steel surface and those in the bulk of the mesh. Some discolouration of the foils took place but this was due to deposited iron corrosion products.

The lack of corrosion attack on the EXPLOSAFE mesh during the simulated cleaning and drying operation is clearly encouraging. However, it must be emphasized that the experiment in no way simulates accurately a real cleaning and drying operation, and does not incorporate possible "additive effects" from repeated cleaning/drying operations.

The implications of the significant corrosion of the steel tank car surface, at areas of contact with the aluminum mesh, must clearly be assessed in terms of the frequency of cleaning/drying operations, their duration and the significance for subsequent operation of the tank car.

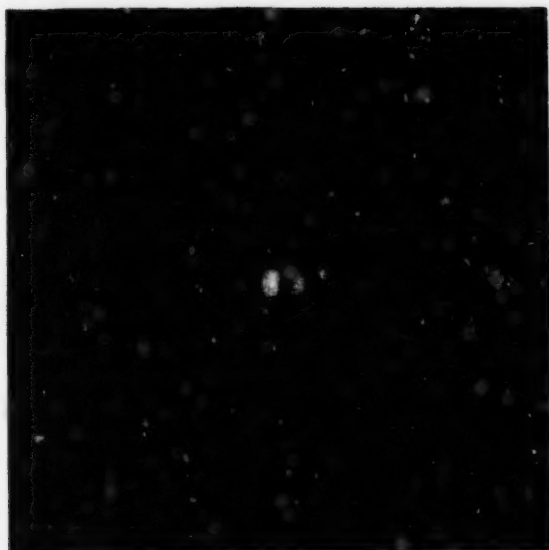


FIGURE A1 (a): SAMPLE A1 SHOWING CORROSION
AT AREAS OF CONTACT BETWEEN
AL FOIL AND STEEL

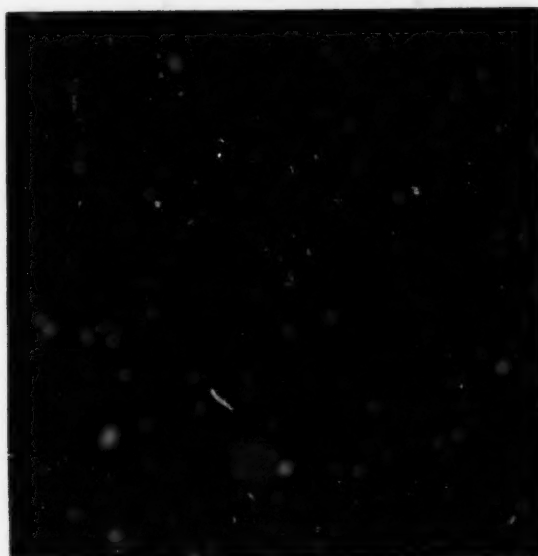


FIGURE A1 (b): SAMPLE A1 SHOWING ABSENCE
OF SEVERE CORROSION ON
SURFACE WITHOUT CONTACT

TABLE A.1

**WEIGHT CHANGE RESULTS ON STEEL PLATES
FROM EXPLOSAFE COMPACT TESTS**

Plate ID No.	Average Mass		W Mass (g)
	Before Test (g)	After Test (g)	
A-1	79.049905	79.060090	0.010185
A-2	79.540827	79.547837	0.007010
B-1	78.914015	78.762433	-0.151582
B-2	79.366870	79.201530	-0.165340

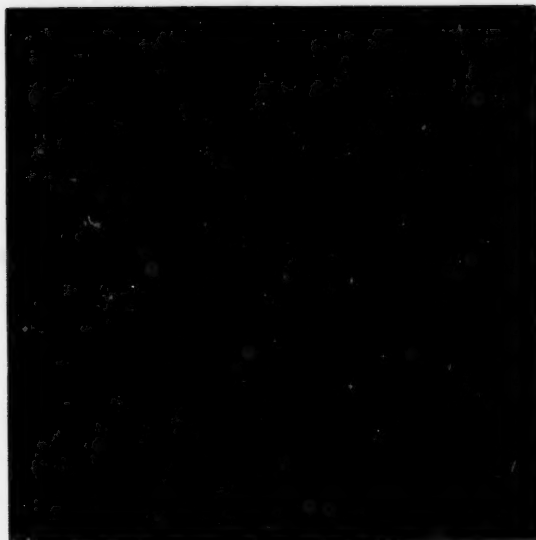


FIGURE A2 (a): SAMPLE B1 SHOWING CORROSION
AT STEAM/WATER INTERFACE -
SURFACE WITHOUT CONTACT

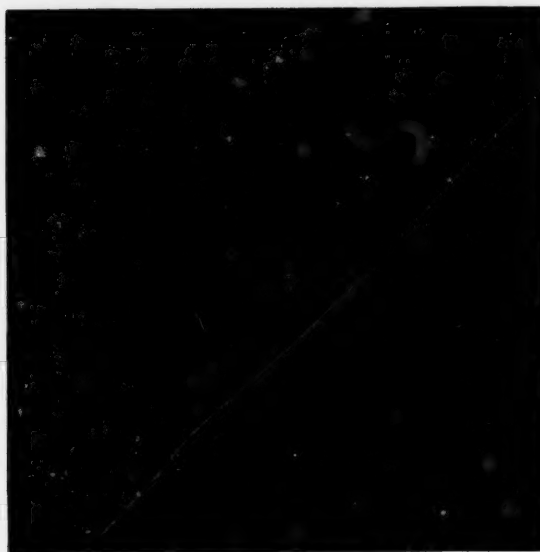


FIGURE A2 (b): SAMPLE B1 SHOWING CORROSION
WITH CONTACT TO AL FOIL

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APPENDIX B

TANK CAR CLEANING



THE CLEANING OF EXPLOSAFE EQUIPPED TANK CARS

SUMMATION

1. Although the present process used to clean unlined tank cars is quite efficient it will not be effective with EXPLOSAFE-equipped cars. The process water is too dirty and the drying procedure will be ineffective.
2. Ignoring the question of impurities, the existing process appears capable of removing the ladings from the aluminum mesh.
3. To clean EXPLOSAFE-equipped cars using the present procedure, the process water would have to be cleaned to remove impurities which could be detrimental to EXPLOSAFE.
4. On the assumption that the earlier portion of the process can be made to work, the mopping up operation will require additional manpower and time, as it is necessary to remove a strip of EXPLOSAFE from along the bottom of the car.
5. The use of complexing agents to remove foreign material from the cars does not look promising. There are potential problems in controlling the complexing reaction and removing the solution from the car.
6. The mechanism used to fasten the EXPLOSAFE to the interior of the car will greatly affect the cost and ability to clean the car. Designs which employ sheet material over the EXPLOSAFE even though some degree of penetration of the sheet may exist will seriously inhibit the cleaning process.

7. The costs incurred to clean an EXPLOSAFE-equipped car will require sizeable capital investment and will mean additional overhead and labor costs. In addition, extra costs will be incurred due to added maintainance and repair operations.

THE CLEANING OF EXPLOSAFE EQUIPPED TANK CARS

The study addressed the ability to clean tank cars equipped with EXPLOSAFE. The problem was approached in the following manner.

- To determine - the effectiveness of the present cleaning process,
- the ability of the present cleaning process to remove the lading from EXPLOSAFE,
 - the ramifications of the use of EXPLOSAFE on the mechanics of the present cleaning process,
 - what changes must be made to the present cleaning process to accommodate EXPLOSAFE,
 - areas of increased costs.

Effectiveness of the Present Cleaning Process

The cleaning process currently used by PROCOR for either single or dual lease LPG or A.A. tank cars has been documented previously [1]. In addition to observing the process first hand, it was desired to assess how effective this process was in cleaning the lading from a car and as well what undesirable residuals might be left in the car. To facilitate this, a series of samples was taken from inside the car. These included scrapings from the wall, crud and residual water samples from the bottom of the tank and a sample of the recycled water used in the cleaning process.

Under the direction of P. McKay, the samples were analysed for several compounds, which, if present in the tank, would be harmful to the EXPLOSAFE material. The results of these tests are shown in Table B.1. The tests indicated that a good percentage of the material found in the car after cleaning comes from the process water. However, there is a good possibility that the ladings may introduce them as well. The source of the copper is not known but it is possible that it may be generated as a corrosion product from the steel used in the tank construction. The steel (TC 128) contains approximately 0.35 percent copper [2].

The source of the crud at the tank bottom is unknown. The crud is comprised primarily of iron along with the materials in Table B.1. However, there are other constituents present which were not identified, such as an oily residue. It is likely that the iron oxide in the crud had been flushed from the tank walls during the cleaning process. In cars which have had longer use between cleaning, such as single lease LPG cars, the crud accumulation is much greater and it is possible that some of it had entered with the ladings.

The present cleaning process is effective in removing the lading from the interior of a conventional tank car. However, the use of recycled water for cleaning introduces a number of contaminants which would cause corrosion of the EXPLOSAFE [3].

The Cleaning of EXPLOSAFE

The objective of this series of scoping tests was to ascertain whether the EXPLOSAFE would present any difficulties in cleaning. The present cleaning process was simulated in a very rudimentary manner to test the process capability of removing A.A. and LPG from the aluminum mesh.

Samples of EXPLOSAFE material consisting of 75 mm cubes were prepared. One piece was immersed in benzene and the other in ammonium hydroxide for twenty-four hours. Benzene was used rather than propane for ease of handling and because a specific test for its presence was already in place, whereas to test for propane would require a new procedure. If the present process could remove the benzene it would certainly remove the more volatile propane. Ammonium hydroxide was used rather than anhydrous ammonia as it is easier to handle and once water is introduced into the tank both in the flushing cycle and steaming process, this is the chemical which would be formed on the surface of the aluminum EXPLOSAFE structure. Both samples were air dried to remove excess liquid and then baked in an oven at 121°C for 3 hours. The heating cycle represents a period equivalent to the time at temperature in the steam cycle. The temperature was an estimate of the average temperature during the steam cycle rather than the peak temperature. The shorter time was arbitrarily selected, as the amount of mesh used in these tests was small compared to that in the actual car. Each sample was then washed in a beaker containing one litre of deionized distilled water.

A 25 mL aliquot of wash water from the ammonium hydroxide sample was analyzed by the Nessler Reagent method for ammonia. No ammonia was detected, therefore the concentration was <0.1 mg ammonia per litre of water.

The amount of benzene in the one litre wash was measured by extracting the benzene from the water into cyclohexane and then analyzing the cyclohexane by spectrophotometry for aromatic compounds. No aromatic compounds were detected therefore the concentration was <0.02 mg aromatic compounds per litre of water.

Although these tests were fairly rudimentary, they showed that the present cleaning process could be used to clean the residual lading from the aluminum mesh and no anomalous behaviour should occur.

These tests did not consider the retention of foreign material in the EXPLOSAFE mesh. There exists a possibility that the presence of these cation and anion impurities shown in Table B.1 could inhibit the complete removal of all the lading from the mesh by tying it up as a compound in areas where they are trapped, such as the tips of the slits in the mesh. Indeed it is possible that if the water used to generate steam is not pure, it will contaminate the EXPLOSAFE.

The Effect of EXPLOSAFE on the Cleaning Process

The present cleaning procedure consists of the following steps;

- a. flaring off residual lading,
- b. water flush - A.A. only,
- c. steaming - 6 to 8 hours,
- d. air drying - 2 to 4 hours,
- e. mopping up and inspection.

An assessment of how the use of EXPLOSAFE would affect the above operations was performed. In the case of the steaming and drying operations a simplified transient thermal analysis of the wall with and without EXPLOSAFE was done to estimate its effect on these processes.

The flaring operation consists of venting the residual gas and liquid remaining in the tank after use. The maximum rate of lading removal is controlled by the rate at which it can be

burned in the flaring stack. The actual rate of vaporization within the car is controlled by the temperature of the car which in turn is a function of the ambient temperature outside the car. The use of an EXPLOSAFE lining should have little or no effect on this operation. In fact, it may prove beneficial by conducting heat from the warmer upper section of the car into the liquid at the bottom. In this instance, the EXPLOSAFE will be acting as it would in an accident situation.

The presence of EXPLOSAFE mesh will have little affect on the water flush of A.A. cars. More water may be needed to absorb the additional A.A. held in the mesh but the time presently required for this operation is not rigidly defined. Therefore the additional time required to add more water would not be significant.

The presence of the mesh will not adversely affect the heating of the tank. In fact transient thermal analysis shows that a car will reach the steam temperature sooner than one without any mesh. More steaming time will be required for the EXPLOSAFE due to the greatly increased surface area of the car interior. As noted previously, the scoping tests showed that there should be no apparent problem in removing the ladings from the surface of the aluminum. Therefore the cleaning time will be primarily a function of the ability of the steam to penetrate the mesh and remove the lading. A big problem could be areas of stagnation within the mesh, where there may be regions with insufficient steam velocity to sweep out the vaporized lading. This is possible because the steam is introduced into the car through the gas valve and its flow is not directed in any particular manner. Thus it is quite possible to have areas of stagnation within the mesh particularly at the extreme ends of the car.

It is difficult to estimate the exact amount of time required to steam clean a tank car containing EXPLOSAFE. The present

steaming times are adequate but it is not known how the present times were determined or the margins that they contain. The net effect of the EXPLOSAFE will probably be to increase the time of this operation by several hours due to the increased surface area in the tank.

The drying operation will take longer in an EXPLOSAFE-lined car. The length of the present method depends on the temperature of the tank and the volume of air passed through it. It is desirable that the car not cool too quickly so that the air flowing into the car has sufficient time to remove the water vapor left in the tank from the steaming process before it condenses out in large quantities. If condensation occurs, it has to be removed manually during the mopping up operation. Normally drying is done outdoors but once the weather becomes cold it is done inside to prevent rapid cooling. The air used in the drying operation whether indoors or out is at ambient temperature and humidity.

This drying procedure will definitely not work when a car is equipped with EXPLOSAFE. The transient thermal analysis of this process suggests that the convective coefficient along the wall of the tank is low, very close to still air conditions. In addition, the aluminum mesh would cause the interior of the car to drop below the saturation temperature of water approximately three times as fast as in the unlined car. The low convective coefficient combined with the rapid drop in temperature would mean a significant amount of condensation would occur within the mesh and the air flow would be insufficient to remove it. A good portion of this condensate would drain to the tank bottom but a large amount would still remain trapped in the mesh. It is the condensate in the mesh which the present drying procedure would not be able to remove in an acceptable amount of time, if at all. On the assumption that the bulk of the mesh could be dried and the remaining water in the car drained to the bottom, it must be removed manually. The final mopping up operation in an unlined

car involves a man entering the car and mopping up any residual water and shovelling up any accumulation of crud along the bottom. At this time a visual inspection is made of the tank to identify any obvious defects which should be repaired prior to the car re-entering service. This procedure usually takes about half an hour.

With EXPLOSAFE in place, the time and difficulty of this operation would be increased. It would likely require an extra man in the car to expedite the operation. The mesh must be removed from the bottom of the car, taken out to clean it of any crud accumulated within its matrix and then dried. The water and sediment on the bottom of the car would be removed while the mesh was processed. The mesh can then be put back into the car and placed in position. No inspection of the tank walls would be possible.

An item that is critical to the time involved in this operation, would be the mechanism used to hold the mesh in place. The more complex this mechanism, the greater the time involved in disassembly and assembly. Our best estimate of the time required to complete this operation using three men instead of the current two, is two hours. Additional drying equipment would also be needed.

Modifications Required to Clean EXPLOSAFE Cars

To clean EXPLOSAFE successfully, the existing cleaning procedure must be modified significantly in certain areas. The first step would be to establish a new set of time and temperature parameters in the steam cleaning phase to ensure that all of the lading is successfully removed from the tank. The use of recycled water for both the flushing and steaming operation introduces foreign material into the tank which would be

detrimental to the aluminum mesh [3]. To avoid this problem the water used in these steps should at least be deionized.

Consideration has been given to the question of additional or alternate methods to remove the impurities from the car. One of these is the use of a complexing agent. This process is more difficult to control than simply using deionized water. The chemistry of the complexing reaction in the tank car must be well controlled in terms of temperature and PH to ensure complexation of all ions in a soluble form. However, a problem is encountered similar to that associated with the steaming, of removing the complexing agent from the car without leaving any behind. It is expected that the complexing agent would be as difficult to remove from the mesh as the water from the steaming process and if there is any toxicity associated with its use there would be additional problems.

There are additional questions as to the effectiveness of using clean process water. There is no doubt that it would prevent the influx of foreign material during cleaning, however, it is not known how much of these impurities are being introduced by the loadings and how much of the crud found in the tank bottom is generated by internal corrosion. This question was addressed previously [4] and it is very important to obtain answers. Even if the cleaning process is made very clean it will be of no avail if the loadings are major sources of contamination.

The drying process may be the most difficult aspect of the present cleaning procedure to modify. As it stands, the present method and equipment will be ineffective for reasons outlined previously. The first essential change, which would help even the present drying equipment work better, would be to use clean, dehydrated warm air (20-35°C) rather than air at ambient temperature and humidity. The selection of the air temperature was somewhat arbitrary and in reality it would have to be set to reduce the potential for corrosion during the drying process.

Some means of scrubbing the air of contaminants should be considered to prevent the entry of deleterious material. In the cleaning procedure witnessed in Edmonton, the air entering the car was sucked in directly from outside and contained the industrial pollutants normally found in city air plus a good dose of hydrogen sulphide blown in from an uncontrolled sour gas well south of the city.

The most difficult aspect of the drying operation is the distribution of the air within the car in such a manner as to generate sufficient turbulence to remove the water vapor or condensate from the inner reaches of the mesh. The present hardware does not appear capable of this. The design of hardware to do this would not be easy as most of the drying should be done when the car is still quite hot so that only a minimum amount of condensation will have occurred. Its design is further limited by the size of the manway and the fact that the car would be too hot for a man to enter to do any set up work.

An additional aspect, which could have a great influence on the ability to clean and dry the car, would be the method used to hold the EXPLOSAFE in place. The covering of the mesh with sheet material as part of the restraint design, even with numerous holes drilled in it, would significantly increase the difficulty of either operation by further inhibiting steam or air flow in and out of the mesh. The use of such a restraint design should be avoided.

In summary, there appear to be significant problems associated with the cleaning of a tank car lined with EXPLOSAFE. Some of these problems can be circumvented by changes in the cleaning process. However, to minimize the entry of foreign material it will be necessary to control the contaminants coming into the cars from the storage tanks. The difficulties associated with this could be insurmountable.

Areas of Increased Costs

The present cost to clean a tank car is \$700.00 to \$800.00 depending on the time required. This time can vary between 12 - 16 hours depending on the initial conditions of the car. The operation requires about 6 - 8 man-hours at a cost per hour of \$50.00 to \$60.00. The difference between the labor costs and total cost is made up of overhead, profit, etc.

To clean an EXPLOSAFE equipped car will entail increased costs both in terms of labor and capital investment. The capital investment that could be necessary, included the following:

- ion exchange columns to produce clean water for steaming
- a system to clean, dessicate and warm the air used for drying
- a system to deliver an adequate volume of controlled air into the car
- equipment needed for washing and drying the mesh removed during the mopping up operation.

Extra costs would be incurred by having a tank car tying up a cleaning station for the additional time required for the steaming, drying and the mopping up operations. Increased costs would also be incurred during the mopping up operation due to the probable requirement for a third man.

One aspect which does not represent a specific cost assigned to the cleaning process is repairs. The cost of repairs to the cars are an additional charge to the user over and above the cleaning cost. Repairs to damaged EXPLOSAFE material and/or restraint mechanisms would be charged to the user.

It is very difficult to estimate the probable cost of cleaning an

EXPLOSAFE-equipped car since the capital costs are not known nor do we have a breakdown on the costs incurred in the various operations of the present cleaning process. It is estimated that the use of EXPLOSAFE could move the cleaning costs to between \$1,000.00 to \$1,500.00.

References

1. D.W. Patterson, Memorandum to A.J. Bosik, Davis Engineering, M&MB-82-249.
2. A.J. Bosik, Davis Engineering, Memorandum to D.W. Patterson, Davis Engineering File No. C82-26.
3. D.W. Patterson, Memorandum to A.J. Bosik, Davis Engineering, M&MB-82-250.
4. D.W. Patterson, Memorandum to A.J. Bosik, Davis Engineering, M&MB-82-276.

TABLE B.1

CATION AND ANIONS PRESENT IN THE TANK CAR
AND IN THE PROCESS WATER

SAMPLE	CATIONS	ANIONS
Crud Sample*	Cu (mg/g) 0.95 +/- 0.3 Na (mg/g) 0.13 +/- 0.01 Ca (mg/g) 2.81 +/- 0.08	
Residual Water in Tank		F (mg/L) 1.6 +/- 0.3 Cl (mg/L) 91 +/- 3 SO4 (mg/L) 28 +/- 2
Process Water	Cu (mg/L) < 0.05 Na (mg/L) 400 +/- 14 Ca (mg/L) 200 +/- 6	F (mg/L) 2.54 +/- 0.18 Cl (mg/L) 14.8 +/- 0.3 SO4 (mg/L) 3450 +/- 250

*The crud sample was considered more likely to be representative of what the car contained than the wall scrapings.

APPENDIX C

CANDIDATE SUPPORT STRUCTURE CONCEPTS

CANDIDATE SUPPORT STRUCTURE CONCEPTS

The support structure design process was initiated with the formulation of several structure concepts. The eventual design proposed is an evolution of these concepts, combining the ideas of two concepts in particular.

These design concepts are documented and discussed in this appendix to aid in the description of the design process. Further, if at a later date it should be decided to seek an alternate final design, this documentation will enable a rapid re-evaluation.

Table C1 presents a summary of the candidate concept evaluation. The evaluation does not include cost as a consideration.

The design presented in Figure 2 combines some features of concepts 5 and 6. The threaded longitudinal rods of concept 6 are used to support the Explosafe radially and the support structure longitudinally. The rods allow for ease of installation and assembly. A variation of the expanded 'T' sections illustrated in concept 6 are used with the base of the 'T' friction fit against the tank wall for increased support of the Explosafe and structure longitudinally. A perforated aluminum skin is included as a design option using much the same format as in concept 5 except the skin is supported by the expanded rings.

None of the candidate concepts gave consideration to the support of Explosafe and a structure in the tank end caps. This factor is considered in the final design.

TABLE C1-CANDIDATE EVALUATION SUMMARY

CONCEPT	FIG(S)	ADVANTAGES	DISADVANTAGES
1. Internal and External rings with expanders	C1	-positive EXPLOSAFE support radially and longitudinally -EXPLOSAFE accessible for cleaning	-difficult to install studs through EXPLOSAFE
2. Reinforcing rod through EXPLOSAFE	C2	-EXPLOSAFE accessible for cleaning	-EXPLOSAFE carries structure weight -difficult to install rods through EXPLOSAFE -EXPLOSAFE batt replacement difficult
3. Spiral fibreglass rod	C3	-reduced corrosion -light weight -easy installation -EXPLOSAFE accessible for cleaning	-no longitudinal EXPLOSAFE support -lack of structure rigidity -high temperatures could cause a problem
4. Internal rings with expanding rings	C4	-positive EXPLOSAFE support -easy installation using identical sections	-EXPLOSAFE carries structure weight -no longitudinal EXPLOSAFE support -sloshing loads could be a problem -cleaning could be difficult

CONCEPT	FIG(S)	ADVANTAGES	DISADVANTAGES
5. Perforated aluminum liner	C5, C6	-sloshing loads reduced -easy installation using interlocking sections -reduced corrosion -easy EXPLOSAFE batt replacement	-EXPLOSAFE carries structural weight -cleaning would be difficult -no longitudinal EXPLOSAFE support -structure itself lacks rigidity -may interfere with EXPLOSAFE thermal action
6. 'T' section and retaining rods	C7	-positive radial EXPLOSAFE support -EXPLOSAFE accessible for cleaning -easy installation and EXPLOSAFE batt replacement using threaded rods	-limited longitudinal support -EXPLOSAFE carries structural weight
7. Cables and retaining plates	C8	-positive radial EXPLOSAFE support -EXPLOSAFE accessible for cleaning -easy installation and EXPLOSAFE batt replacement using tensioned cables	-limited longitudinal support -cable sag could reduce wall contact -cable tension must be carried by tank wall
8. Concentric inner liner	C9	-no modifications to cleaning process required -sloshing and corrosion reduced	-EXPLOSAFE carries liner weight -may interfere with EXPLOSAFE thermal action -difficult to fabricate

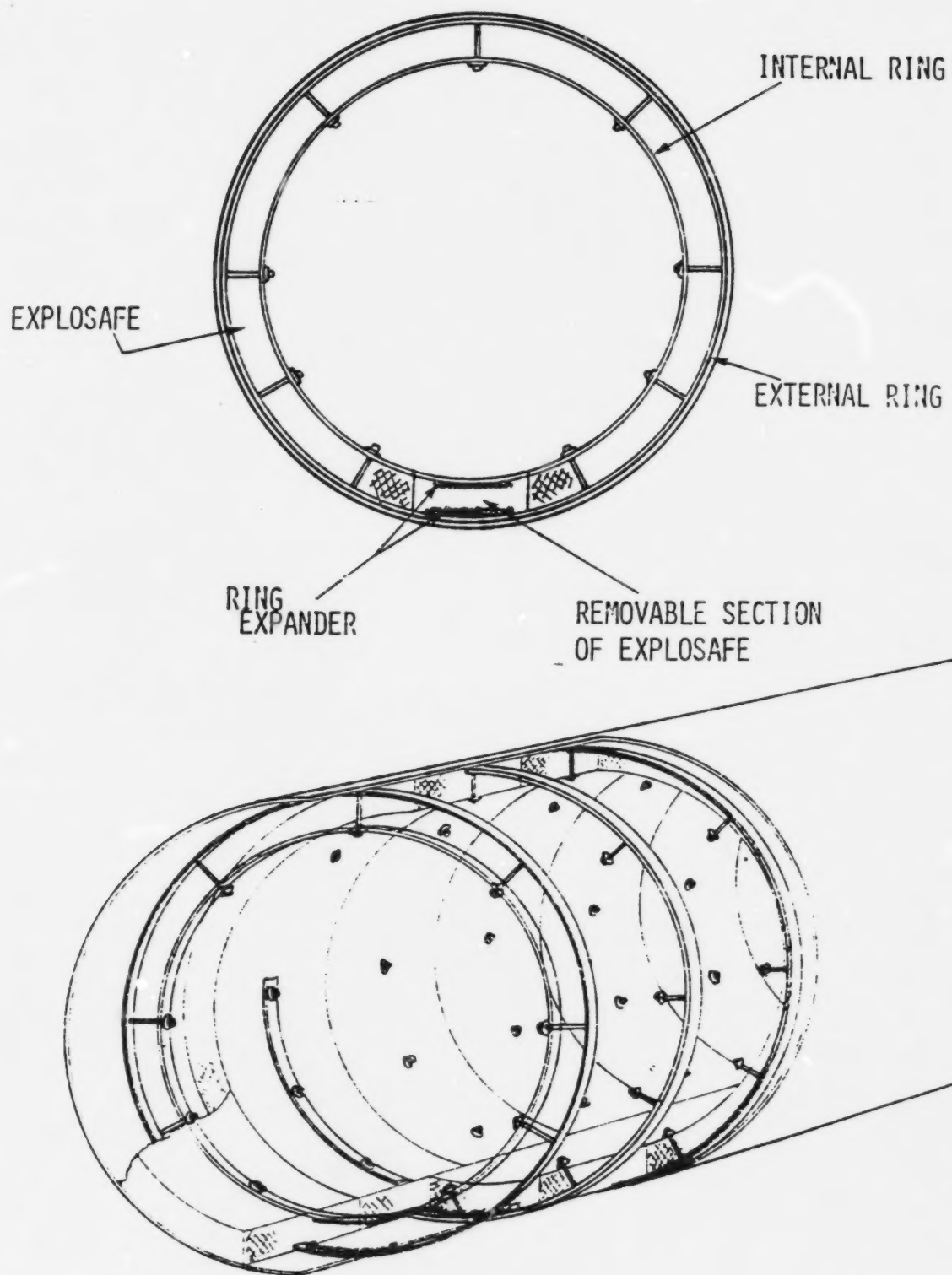


Figure C1- INTERNAL & EXTERNAL RINGS WITH EXPANDERS

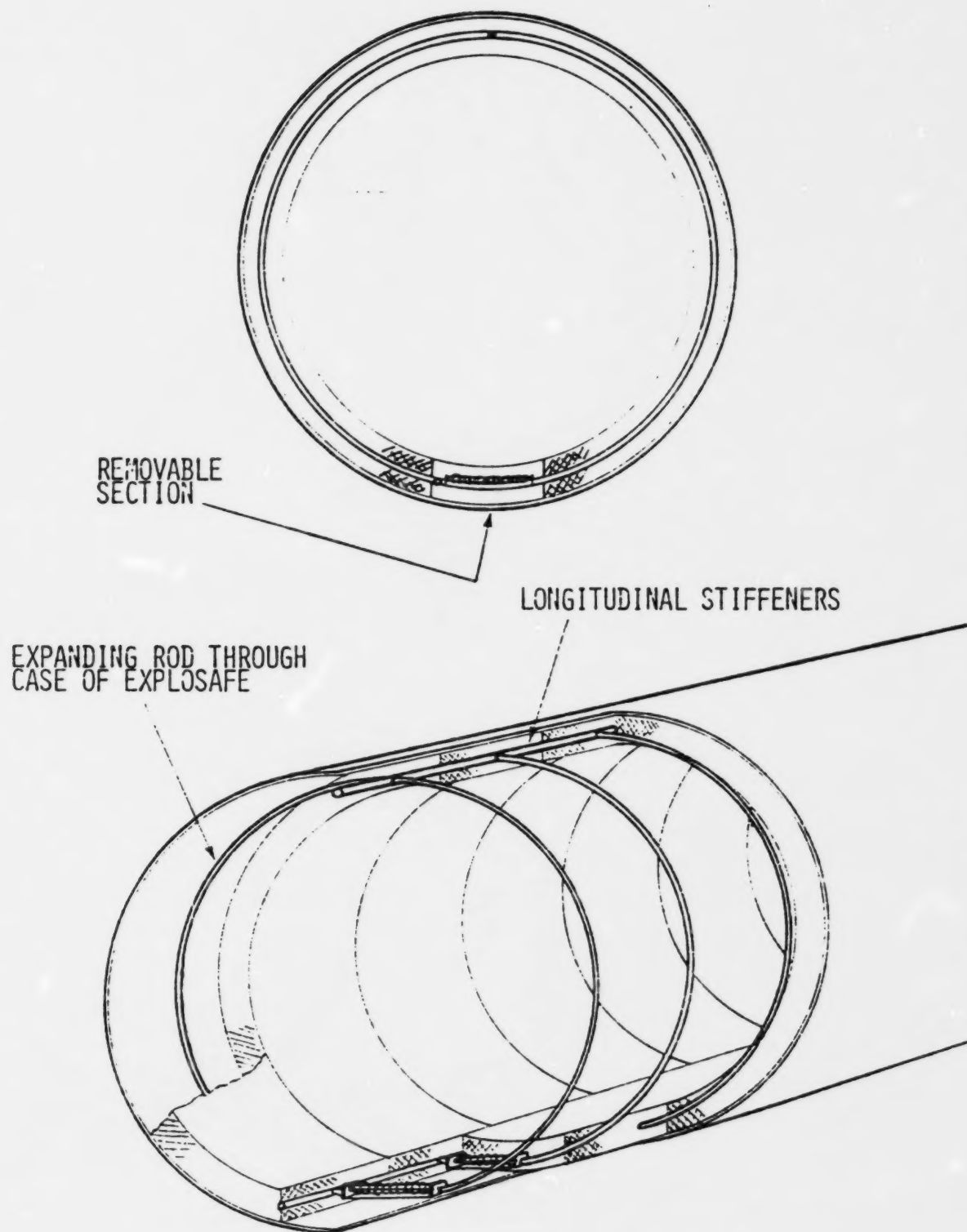


Figure C2 - REINFORCING ROD THROUGH EXPLOSAFE

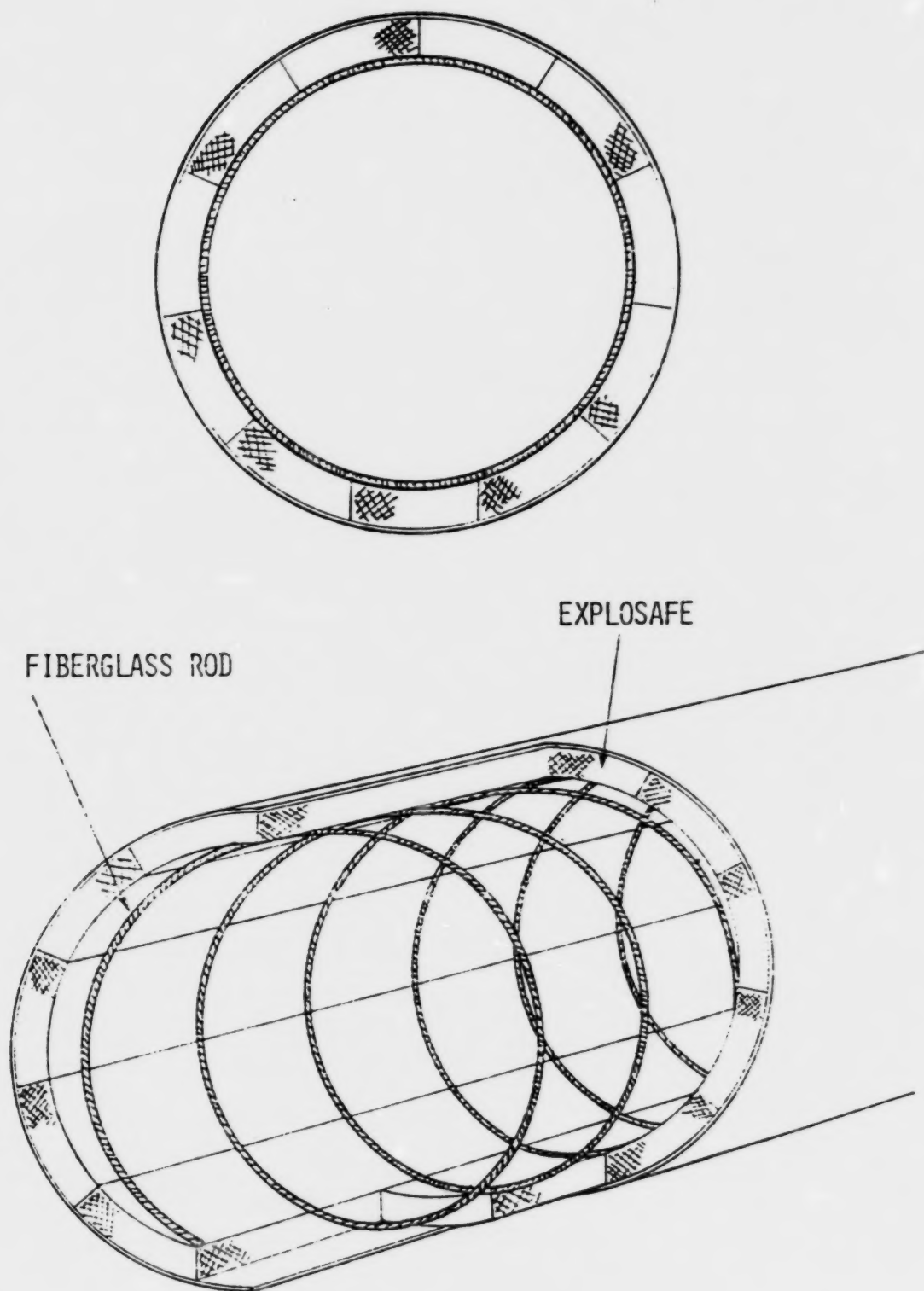


FIG. C3 - SPIRAL FIBERGLASS ROD

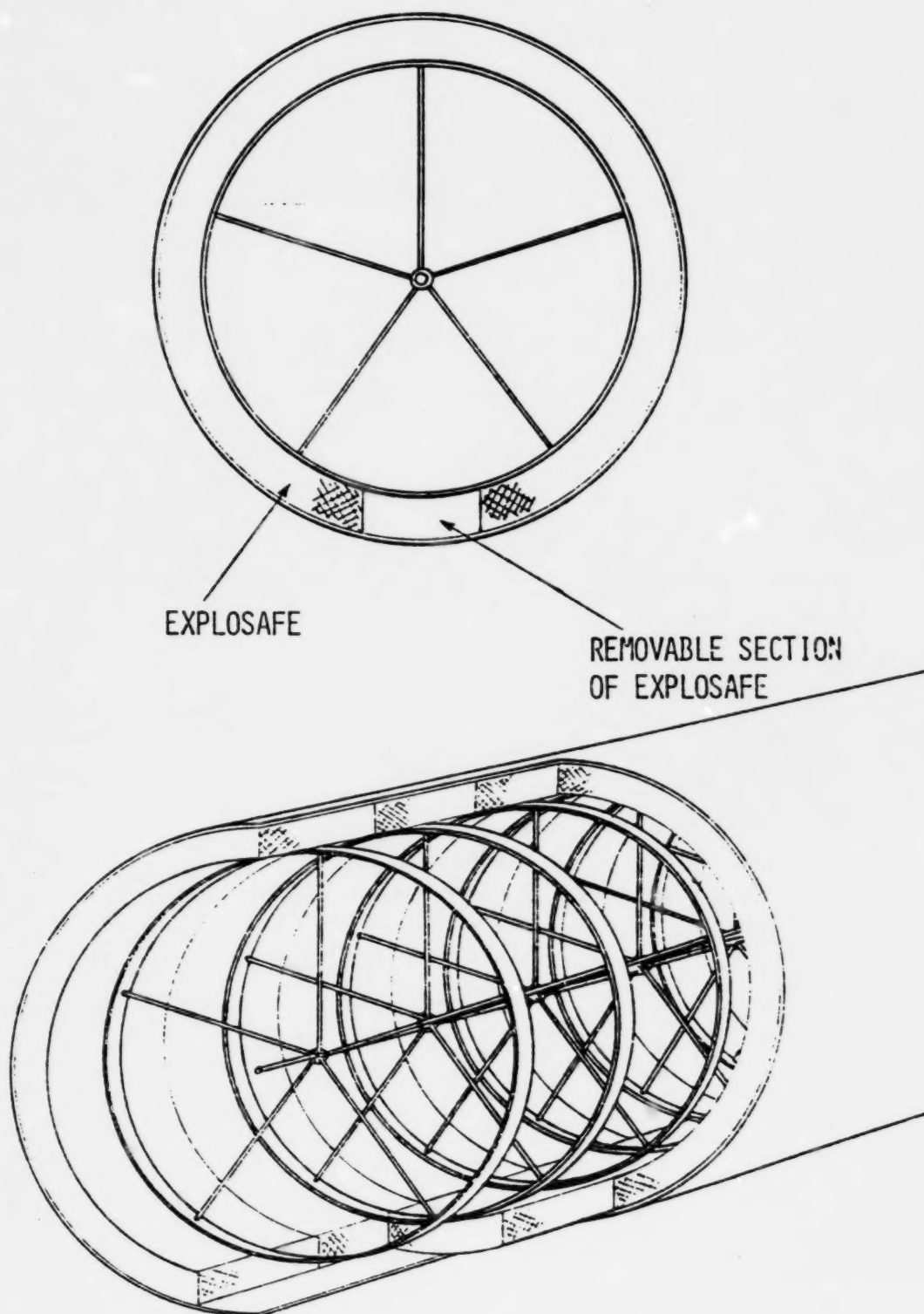


FIG. C4- INTERNAL RINGS WITH EXPANDING STRUTS

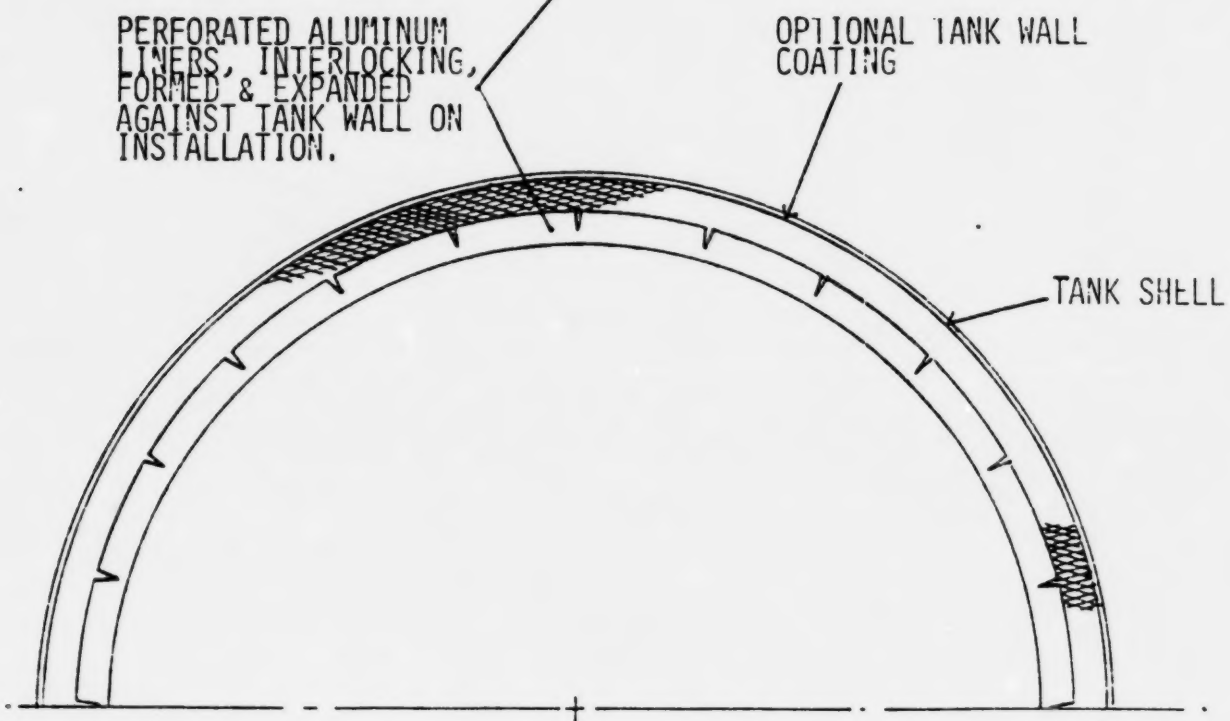
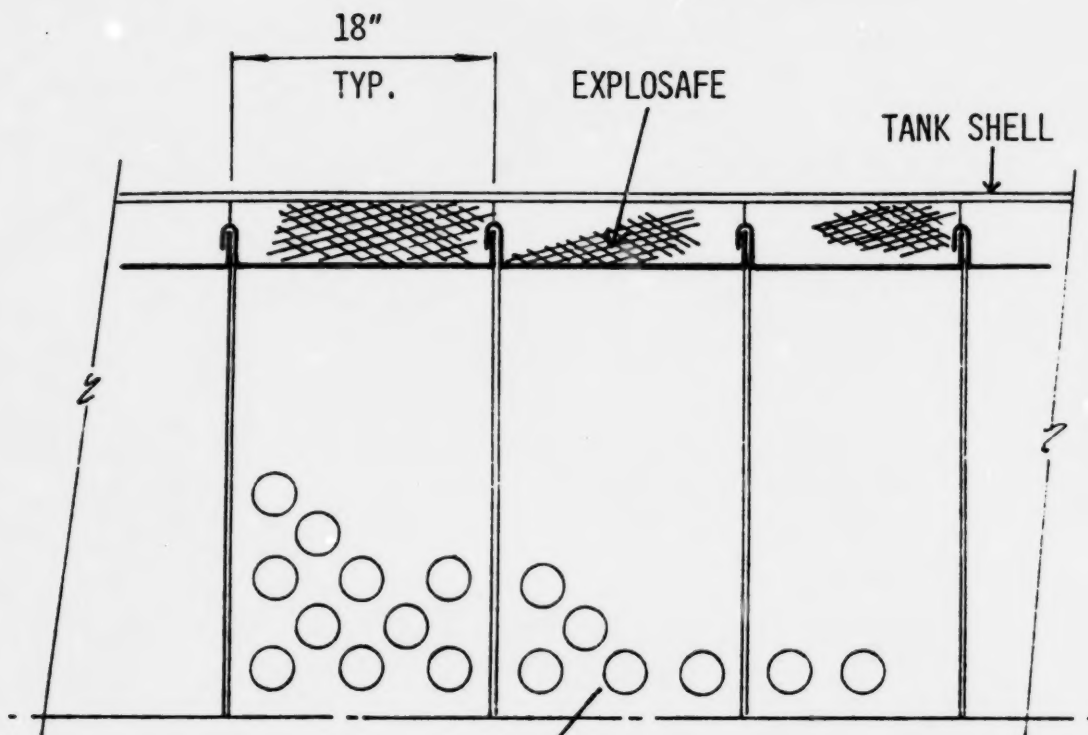


Figure C5 - PERFORATED ALUMINUM LINER

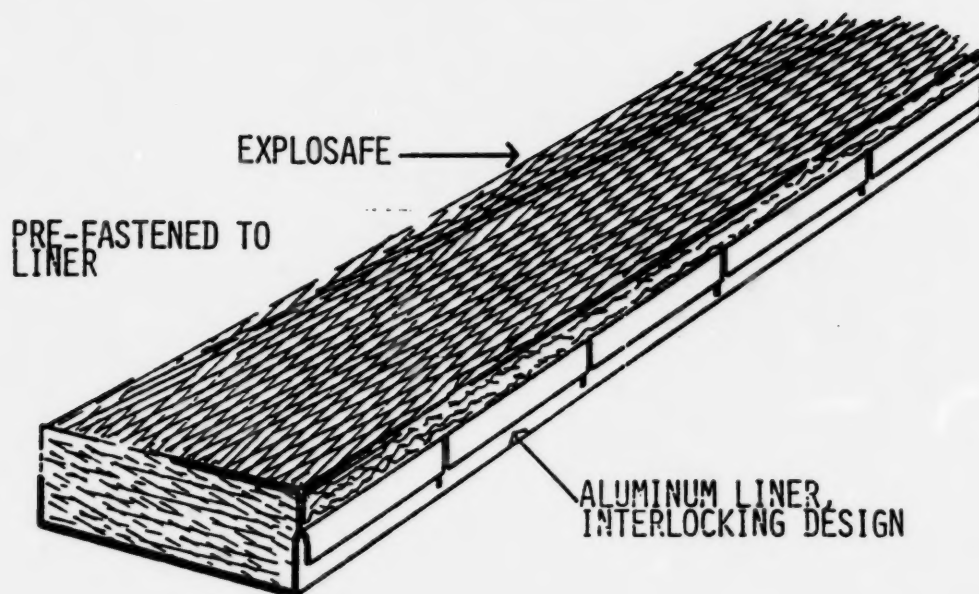


FIG. C6 - TYPICAL FLAT SECTION PRIOR TO
INSTALLATION

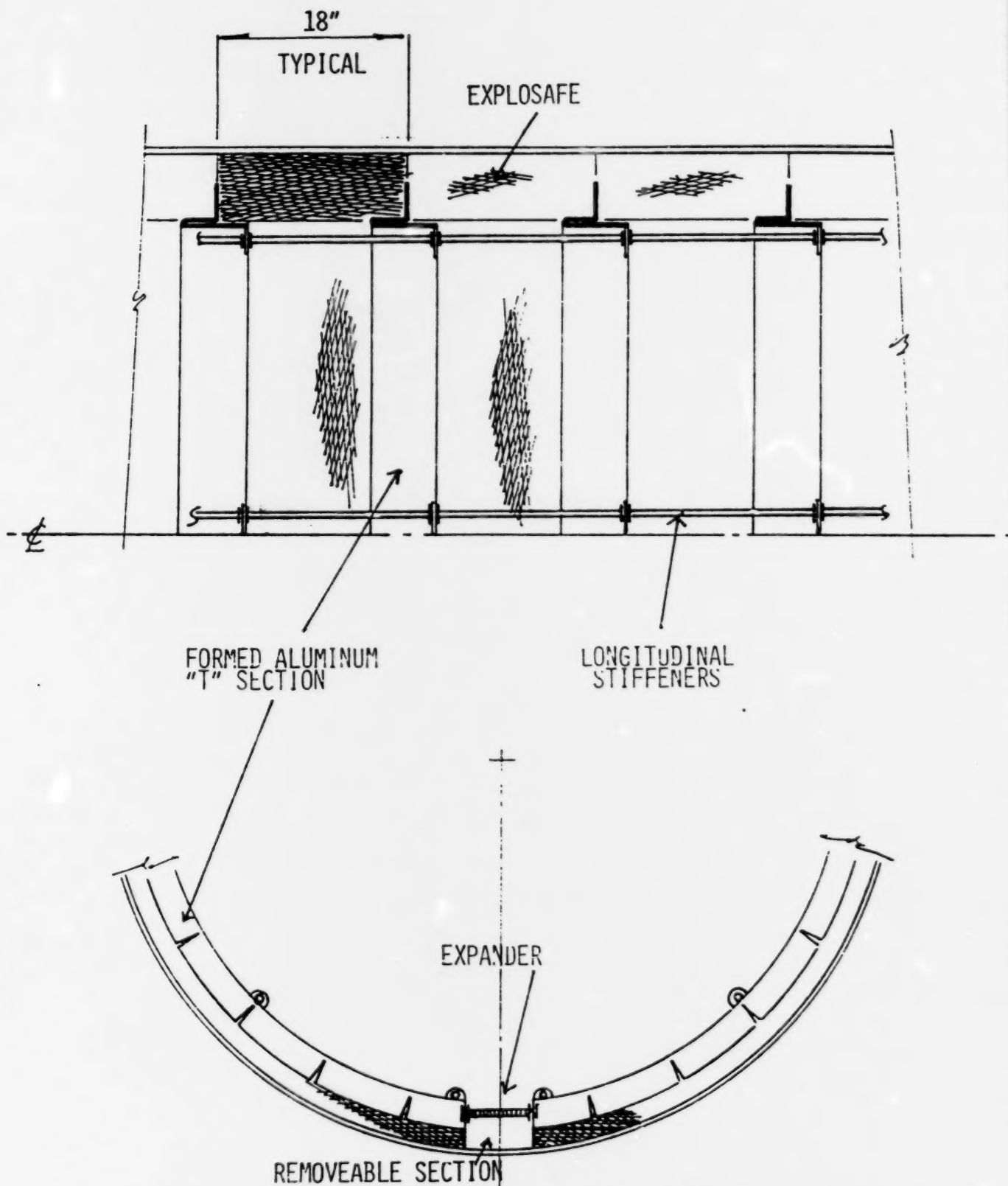


Figure C7 - "T" SECTION AND RETAINING RODS

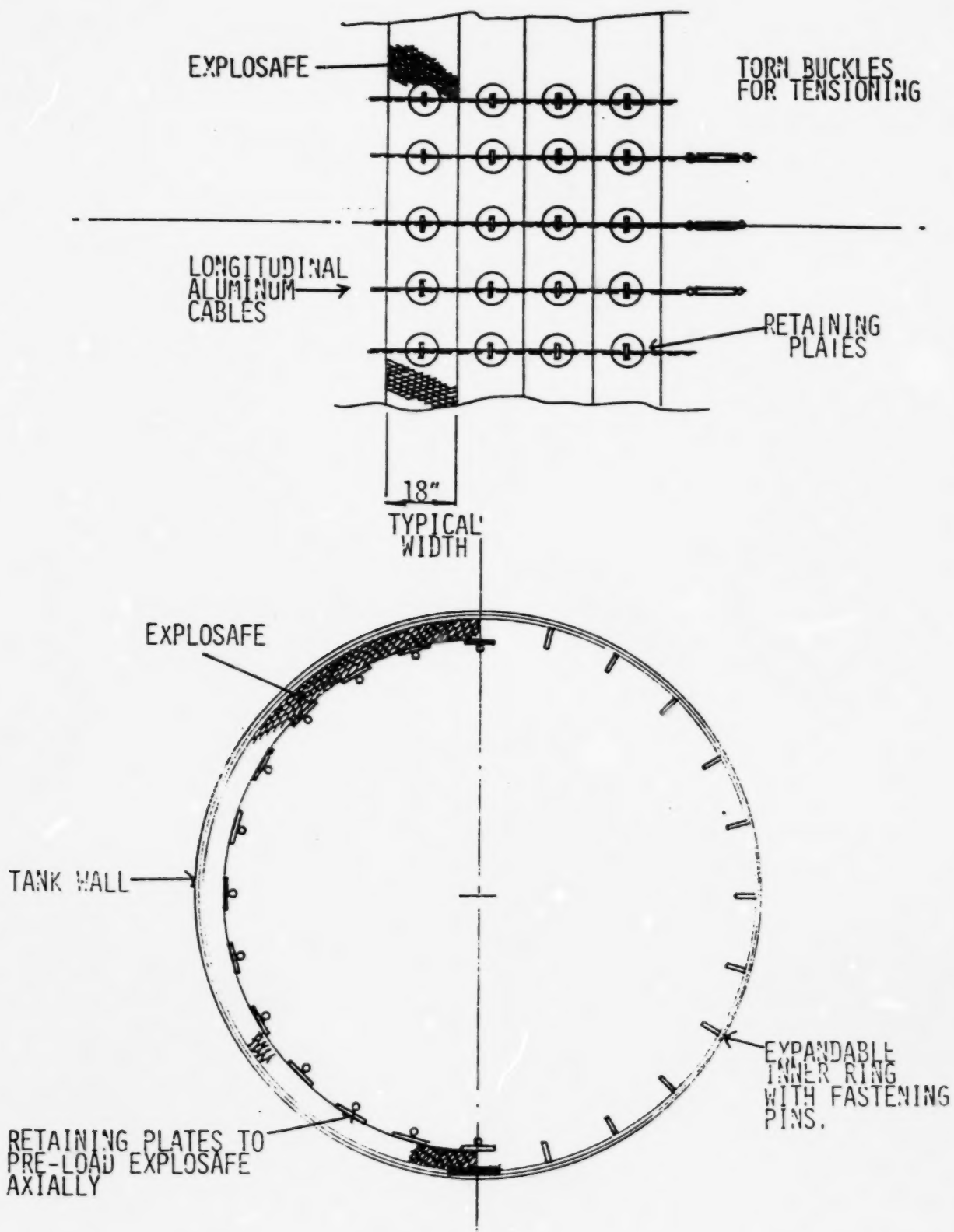


Figure C8 - CABLES AND RETAINING PLATES

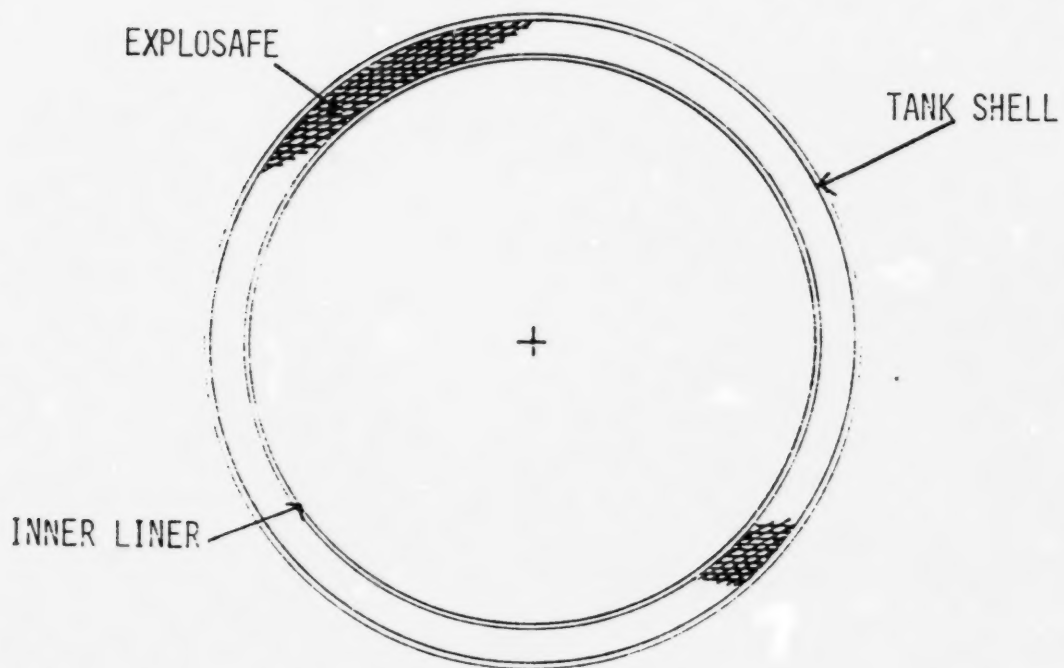
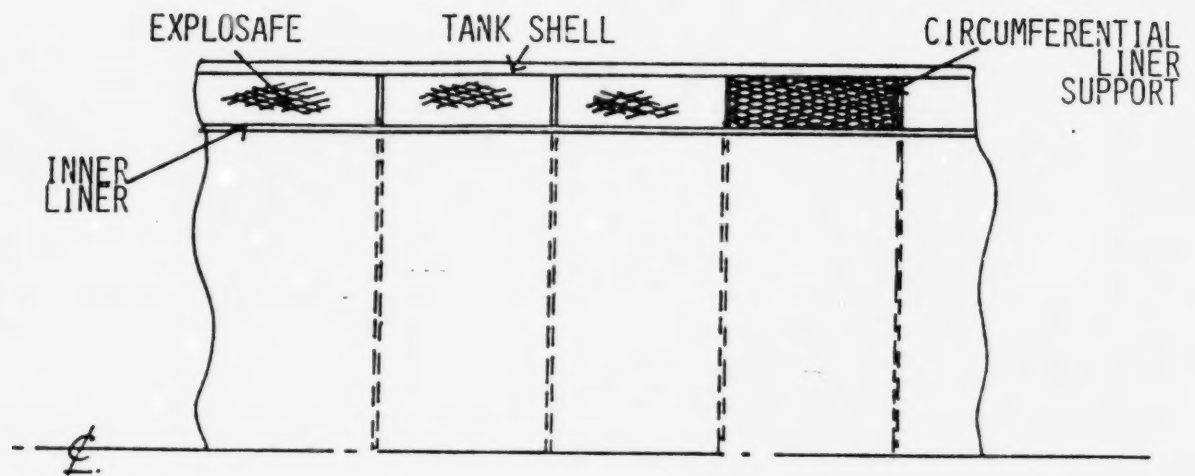


Figure C9- CONCENTRIC INNER LINER

APPENDIX D

CORROSION LABORATORY TESTS

1.0 PRELIMINARY CHEMICAL ANALYSIS

A prerequisite to the main Laboratory Corrosion Testing Program should be a limited program to carry out sampling and chemical analysis of ladings, from various sources, to characterize the nature and quantities of impurities that are present. In particular the range of concentration of H_2O and Cl^- should be known (A.A. and LPG). There should also be some work carried out to characterize the cleaning process. This program would provide data on the quantities of impurities introduced into tank cars from the ladings and the cleaning operations.

2.0 CORROSION ENVIRONMENTS

2.1 A.A.

The objective would be to obtain accurate corrosion rate data on 3010 aluminum in galvanic contact with the tank car steel, as a function of the impurity content in the ladings. The impurities identified as being of major importance are H_2O and Cl^- and the tests would aim at establishing the change of corrosion rate with H_2O and Cl^- concentrations in a range typical of that found in the ladings. The effect of temperature on corrosion rate would receive limited study. Control experiments would be run to measure the corrosion behaviour in a sample of the lading (known impurity content) and in pure A.A.

2.1.1 Procedure

The corrosion samples used would be similar to those used in the preliminary corrosion program and would consist of layers of Explosafe mesh compressed between plates of tank car steel. The corrosion samples would be type 3010 aluminum foils, cleaned and accurately weighed, interspersed at different points

through the thickness of the mesh. These would provide data on the possible variation of galvanic corrosion rate with distance from the steel surface. These assemblies would then be exposed to the following A.A. environments contained in stainless steel pressure vessels at the temperatures and for the times indicated.

Environment	Test temp. (°C)	Time (months)	No. samples
1. A.A.	25	3	1
2. A.A. + H ₂ O (min)	25	3	1
3. A.A. + H ₂ O (max)	25	3	1
4. A.A. + H ₂ O (max) + Cl ⁻ (max)	25 and 60	3	2
5. A.A. + H ₂ O (max)	25	3	1
6. A.A. + H ₂ O (min) + Cl ⁻ (min)	25	3	1
7. A.A. sample from lading	25	3	1

Note

The max. and min. refer to ranges of these impurities identified by the preliminary analysis of the ladings.

A detailed metallographic examination of the foils and steel plates would be carried out following the exposures.

2.2 LPG

As was discussed previously (Section 2.5), water in LPG most probably exists as a separate phase, and salts present as impurities in the ladings will partition into the aqueous phase. Corrosion would be expected to occur predominantly in the aqueous phase. Therefore, to study the effect of water in LPG on an

experimental scale, it would be necessary to use mixtures with a greater water fraction to those found in the ladings in order to simulate the much larger quantities of water which would separate at the bottom of a tank car. The same $\text{Cl}^-:\text{H}_2\text{O}$ ratio as found in the ladings would be maintained in these mixtures.

2.2.1 Procedures

The test specimens would be identical to those described in procedure 2.1.1. Samples would be exposed in the following environments contained in pressure vessels at the temperatures and for times shown.

Environment	Test temp. (°C)	Time (months)	No. samples
1. LPG	25	3	1
2. LPG + 10% H_2O + Cl^-	25	3	1
3. LPG + 50% H_2O + Cl^-	25 and 60	3	2
4. LPG sample of lading (from bottom of tank car if possible)	25	3	1

A detailed metallographic examination would also be performed on these samples following a run.

3.0 CLEANING AND DRYING OPERATIONS

3.1 Cleaning

The preliminary corrosion test indicated that accelerated attack occurred during a simulated cleaning. Subsequent examination of samples revealed marked corrosion of the steel plate at points of contact with the Explosafe mesh. This attack

was considered to be the result of rapid crevice corrosion of the steel in the elevated temperature cleaning water. This water had a quality typical of that used for steam cleaning of cars and contained several thousand ppm of SO_4^{2-} and about 100 ppm Cl^- . It is proposed that some additional studies should be performed to characterize this attack and in particular to demonstrate methods of alleviating it.

3.1.1 Procedures

The same sample design to that described in procedure 2.1.1 would be used; however, in addition, small plate samples of the steel would also be exposed. These samples would act as references.

The following conditions would be studied:

Environment	Test temp. (°C)	Time (h)	No. samples
1. Tank car cleaning water	160	6	2
2. Tank car cleaning water	160	10	2
3. Demineralized cleaning water	160	10	2

The cleaning water would be analyzed for Cl^- , SO_4^{2-} , etc. before and after demineralization.

3.2 Drying

The object of these tests would be to assess the likelihood of accelerated corrosion on Explosafe foil and tank car steel by hot concentrated salt liquors formed during the drying operation on tank cars. The extent of corrosion caused by a saturated salt liquor, formed on a metal surface during

evaporation, will depend on both the temperature of the surface and the total time the aqueous phase persists before complete dry-out occurs. During drying, the temperature of the metal surfaces will be decreasing with time; this in turn will slow down the rate of evaporation and increase the time for which a salt liquor can persist. Clearly, controlled experiments to assess corrosion during drying would be very difficult to carry out due to the difficulties of reproducing the actual heat and mass transfer conditions in a tank car during the drying operation.

3.2.1 Procedure

As an alternative to attempting to simulate a drying operation, it is proposed that a series of corrosion experiments could be performed in aerated saturated salt liquors, contained in pressure vessels, to assess the extent of corrosion in this environment at different times (minutes to hours), at a series of temperatures in the range encountered during drying of tank cars. From this data, the exposure time, at each temperature, necessary to produce a specified degree of corrosion (e.g., time to initiate pitting), can be determined. These times and temperatures can then be compared with the time-temperature behaviour of the Explosafe installation, during drying of the tank cars, to estimate the chances of corrosion attack. Clearly, the data would be conservative as it assumes that a saturated salt solution exists at all times and temperatures during drying.

It is proposed that the composition of the saturated salt solution could be inferred from the composition of the water used in the cleaning operation.

The number of experiments at each temperature would have to be a minimum of three and the number of temperatures also a minimum of three.

4.0 FACILITIES, TIME AND PERSONNEL REQUIREMENTS

For the proposed experiments in A.A. and LPG, pressure vessels would be required (preferably stainless steel). The total duration of the program would clearly be related to the number of vessels available. With a total of fourteen vessels, this could be completed in about 6 months (including reporting). With only seven vessels available, it would take about twice the time.

The experiments to assess corrosion during cleaning and drying would have to be carried out in pressure vessels in electrically heated ovens, equipped with suitable controllers for maintaining constant temperature. A minimum of three vessels (preferably high nickel-based alloy) would be required, each fitted with PTFE pressure vessel liners.

The duration of these experiments would not influence the total time for completion of the program.

4.1 Time and Personnel

A breakdown is shown below in terms of the tasks to be performed. The support effort relates mainly to the machining of samples and metallographic work.

Task	Prof. (days)	Technologist (days)	Support (days)
1. A.A.	5	30	5
2. LPG	5	30	5
3. Cleaning	3	8	3
4. Drying	3	21	5
5. Reporting	15		

It does not include an estimate of the time and personnel requirements to carry out the preliminary chemical analysis on loadings.

5.0 ESTIMATED COST

The estimated costs include charges for Technical staff, project management and disbursements (travel, specimen fabrication and pressure vessel operational charges). The labour estimates are based on 1983/84 WNRE rates:

a. Technical	\$63,300
b. Management	\$ 5,000
c. Disbursements	<u>\$ 4,000</u>
Total	\$72,300

APPENDIX E

SUPPLEMENTAL SLOSHING TEST PROGRAM

SUPPLEMENTAL SLOSHING TEST PROGRAM

1.0 INTRODUCTION

The intent of the supplemental sloshing test program is to quantify the effects of the sloshing phenomenon. It is proposed that this be done in two sub-tasks.

Task 1: Analytical Model

An analytical model of the sloshing will be formulated to describe the fluid motion within a tank car. The model will provide critical fluid velocities in a tank under the worst environmental conditions.

Task 2: Experimental Tests

Experimental tests will then be carried out to determine the skin friction coefficient of the EXPLOSAFE as well as forces imposed by fluid penetrating the dry matrix.

With the results of tasks 1 and 2, the fluid dynamic forces on the installation can be quantified and system refinements incorporated where necessary.

2.0 ACTIVITIES

The various project activities are costed in Table E1 scheduled in Figure E1 and described below:

2.1 Project Management

This activity is for the overall coordination, control and management of the project.

2.2 Analytical Model Formulation

This activity will comprise the development of a mathematical description of the sloshing mechanism. It is anticipated that a first order analysis can be largely accomplished manually however some computer time has been allotted.

2.3 Analysis of Results

Model results will be analysed for various input tank accelerations, liquid heights, impact conditions etc...

2.4 Reporting

A short technical report will be prepared following the analysis presenting the results in an organized fashion.

2.5 Formulation of Experimental Tests

Utilizing the results of the analytical model, methods and test apparatus will be devised to obtain experimentally the skin friction coefficient (C_f) and force characteristics of flow through the dry mesh. Proposed test set-ups to acquire the necessary data are illustrated in Figure E2 (a) and E2 (b).

Figure E2 (a) is a postulated method of obtaining the EXPLOSAFE skin friction coefficient. The test involves flow of water through a pipe lined with EXPLOSAFE. By measuring the pressure drop with a manometer the C_f can be obtained. It is estimated that a flow length of 6 m may be required.

Figure E2 (b) demonstrates conceptually how the fluid penetration through dry mesh may be handled. An oblique jet of velocity " v " (as determined from the analytical study) can be impinged upon an EXPLOSAFE batt at a variable angle " θ " (also

obtained from model) and the resulting normal and tangential forces measured. The EXPLOSAFE should be supported in the vertical direction by a steel grid so as not to impede the normal flow.

2.6 Fabrication of Test Apparatus

Experimental set-ups would be fabricated in this activity in preparation for the tests conceived in the previous task.

2.7 Experimental Test Program

The test program would be carried out in this activity obtaining all essential data for the analysis.

2.8 Analysis of Results

The results of the experimental tests will be analyzed and the relevant EXPLOSAFE parameters determined.

2.9 Reporting

Monthly progress reports will be submitted describing the progress of all project tasks.

A final report will be prepared at the conclusion of the study documenting the results.

3.0 COSTS AND SCHEDULE

The total project cost is estimated at \$19,000 with the breakdown as shown in Table E1. The total project duration is anticipated to be 4 months as illustrated in Figure E1.

4.0 IMPLEMENTATION

It is proposed that the analysis and experimented work be conducted with the use of Prof. Sjolander of Carleton University as a sub contractor in the area of fluid mechanics. The analysis should be of sufficient thoroughness to describe the formation of jets on the ends of tank walls during sudden impacts.

The experimental study would be conducted by a qualified mechanical engineering firm. There are a few recommendations to be made in order to ensure accurate results. The manometer tube in the skin friction test should be inserted several pipe diameters inside the span of the EXPLOSAFE liner in order to avoid fluid disturbances caused by end effects. The effective flow path length required to produce accurately measureable pressure drops is approximately 6 m based on an estimated Cf.

In the jet impingement test, care should be taken to ensure that the jet does not contact any body other than the EXPLOSAFE (such as container walls).

SUPPLEMENTAL SLOSHING TEST PROGRAM

TABLE E1 ACTIVITY COST BREAKDOWN

No.	ACTIVITY	COST (\$1000)		TOTAL
		LABOUR	DISBURSEMENTS	
2.1	Project Management	1000		1000
2.2	Analytical Model Formulation	2000	1200	3200
2.3	Analysis of Results	1500	-	1500
2.4	Reporting	1200	100	1300
	Test 1 Subtotal	<u>5700</u>	<u>1700</u>	<u>7400</u>
2.5	Formulation of Experimental Tests	1500	500	2000
2.6	Fabrication of Test Apparatus	3000	1500	4500
2.7	Experimental Test Program	2000	500	2500
2.8	Analysis of Results	1000	-	1000
2.9	Reporting	1500	100	1600
	Test 2 Subtotal	<u>9000</u>	<u>2600</u>	<u>11600</u>
	TOTAL	14700	4300	19000

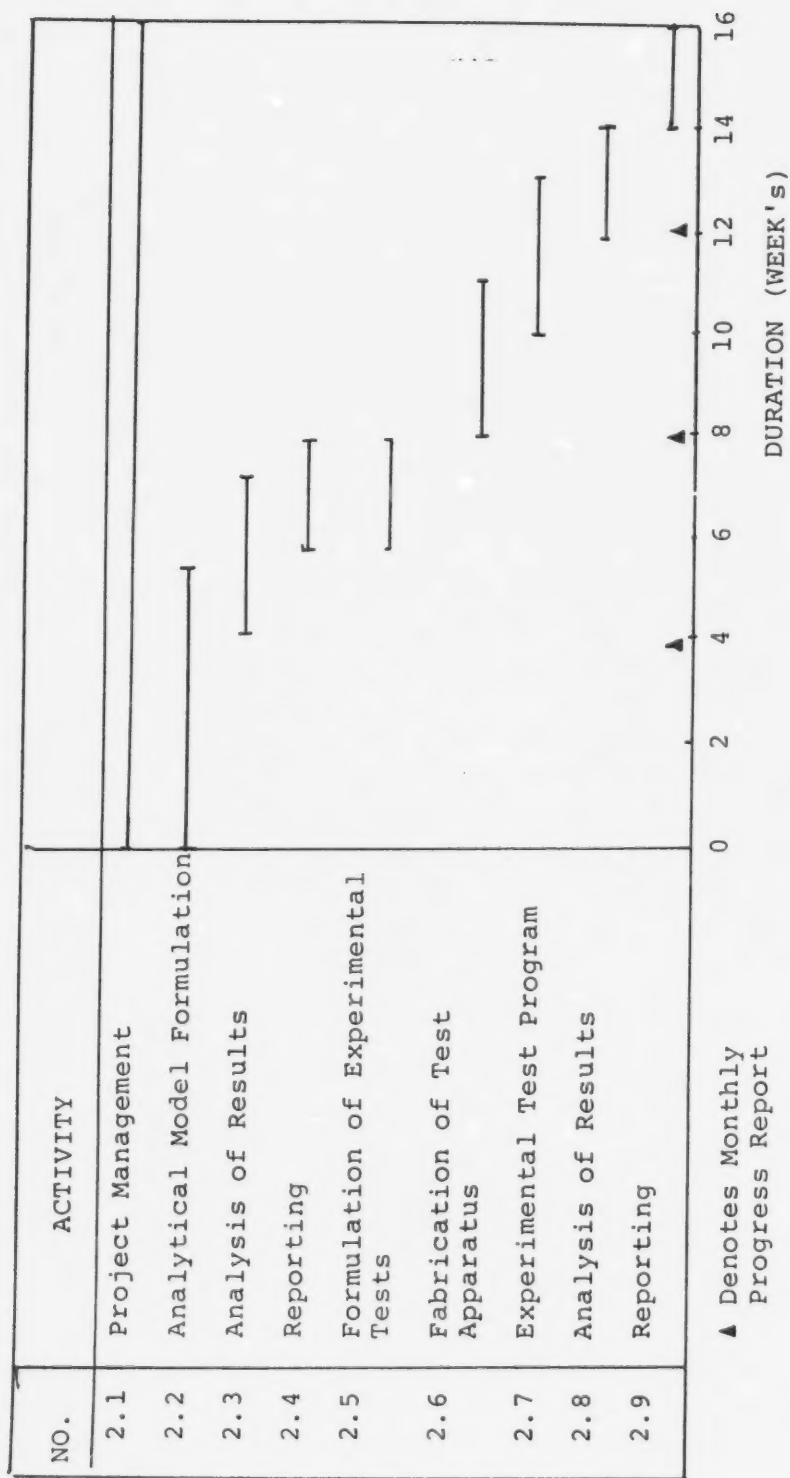
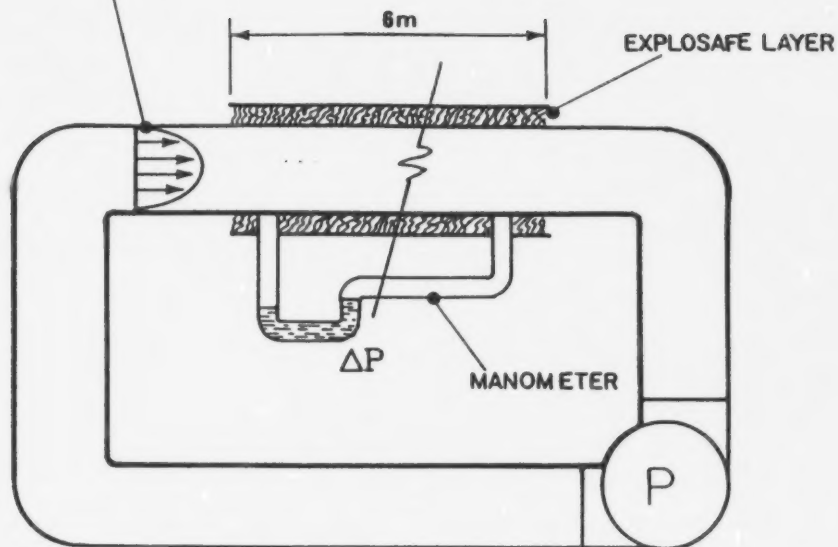
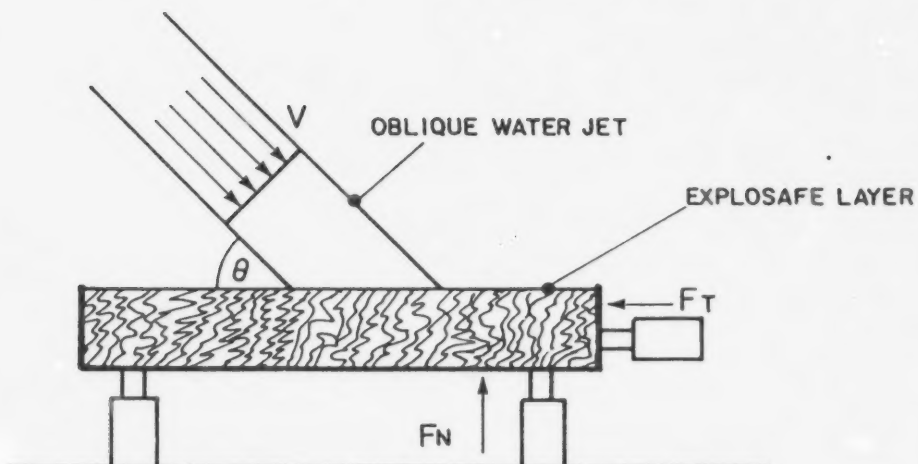


FIGURE E1 - SUPPLEMENTAL SLOSH TEST SCHEDULE

FULLY DEVELOPED FLOW



(a) SKIN FRICTION COEFFICIENT APPARATUS



(b) OBLIQUE JET IMPINGEMENT APPARATUS

FIGURE E2 - EXPERIMENTAL TEST APPARATUS

APPENDIX F

REDEFINITION OF SUPPORT SYSTEM

REDEFINITION OF SUPPORT SYSTEM

1.0 INTRODUCTION

Based on the results of the supplemental test programs, a trial design will be selected. A decision will be based on the cost analysis of this design. The stress analysis of the selected design will be performed to identify the critical stress areas and/or modify the design if necessary. Following the stress analysis, the design will be finalized and detailed.

2.0 ACTIVITIES

The various activities shown in Table F1 and Figure F1 are discussed below.

2.1 Project Management

This activity is for the overall coordination, control and management of the project.

2.2 Review of Supplemental Test Programs

The test programs on corrosion and sloshing will be reviewed and the results will be used to select a feasible design.

2.3 Selection and Cost Analysis of Design

As a result of the review, a design of the support system will be chosen and the cost of material, fabrication and installation will be estimated. A GO/NO-GO decision will depend on this cost estimate.

2.4 Stress Analysis

In this task, the refinement in the sizing of the components of the selected design of the support system will be done by performing the stress analysis. The analysis will utilize the loads generated by the fluid forces due to slosh as predicted in the slosh tests. Due to the complex geometry of the end caps and the conforming support system, a finite element technique may possibly be considered to do the stress analysis.

The main objective of this task is to substantiate the mechanical integrity and to clearly identify those critical areas of the design which might be stressed to critical levels under different loading conditions. These results will also be utilized for the instrumentation of the full scale test car; both for impact and road (or fatigue) tests.

2.5 Detailed Design of the Support System

As a result of the above tasks, a detailed design will follow which will include drawings and installation procedures for the final design. This task will be the final step in the redefinition of the support system.

2.6 Final Report

A final report will be prepared at the conclusion of the study documenting the various tasks of the project.

3.0 COST AND SCHEDULE

The estimated cost of this project is \$58,000.00 and the time estimate is 9 weeks. The details are presented in Table F1 and Figure F1.

4.0 IMPLEMENTATION

Implementation of all the activities will be done by a qualified mechanical engineering firm. However, Activity 2.4 can also be performed by any commercial computing agency which has in house finite element expertise for stress analysis.

5.0 REPORTING

A progress report will be submitted on the status of the project a period of one month following initiation of the project.

TABLE F1
REDEFINITION OF SUPPORT SYSTEM

NO.	ACTIVITY	Cost (\$ 1000)			TASK ASSIGNED TO
		Labour	Disburse- ments	Total	
2.1	Project Management	4.0	-	4.0	ME
2.2	Review of Supple- mental Test Programs	1.5	-	1.5	ME
2.3	Selection and Cost Analysis of Design	3.0	-	3.0	ME
2.4	Stress Analysis	12.0	10.0	22.0	ME, CU, OTHER
2.5	Detailed Design: Drawings and In- stallation Specs.	20.0	-	20.0	ME
2.6	Final Report	7.0	.5	7.5	ME
	Total	47.5	10.5	58.0	
	ME-Qualified Mechan- ical Engineering Firm				
	CU - Carleton Univ.				
	Other- [Commercial Computing Agency with F.E Expertise]				

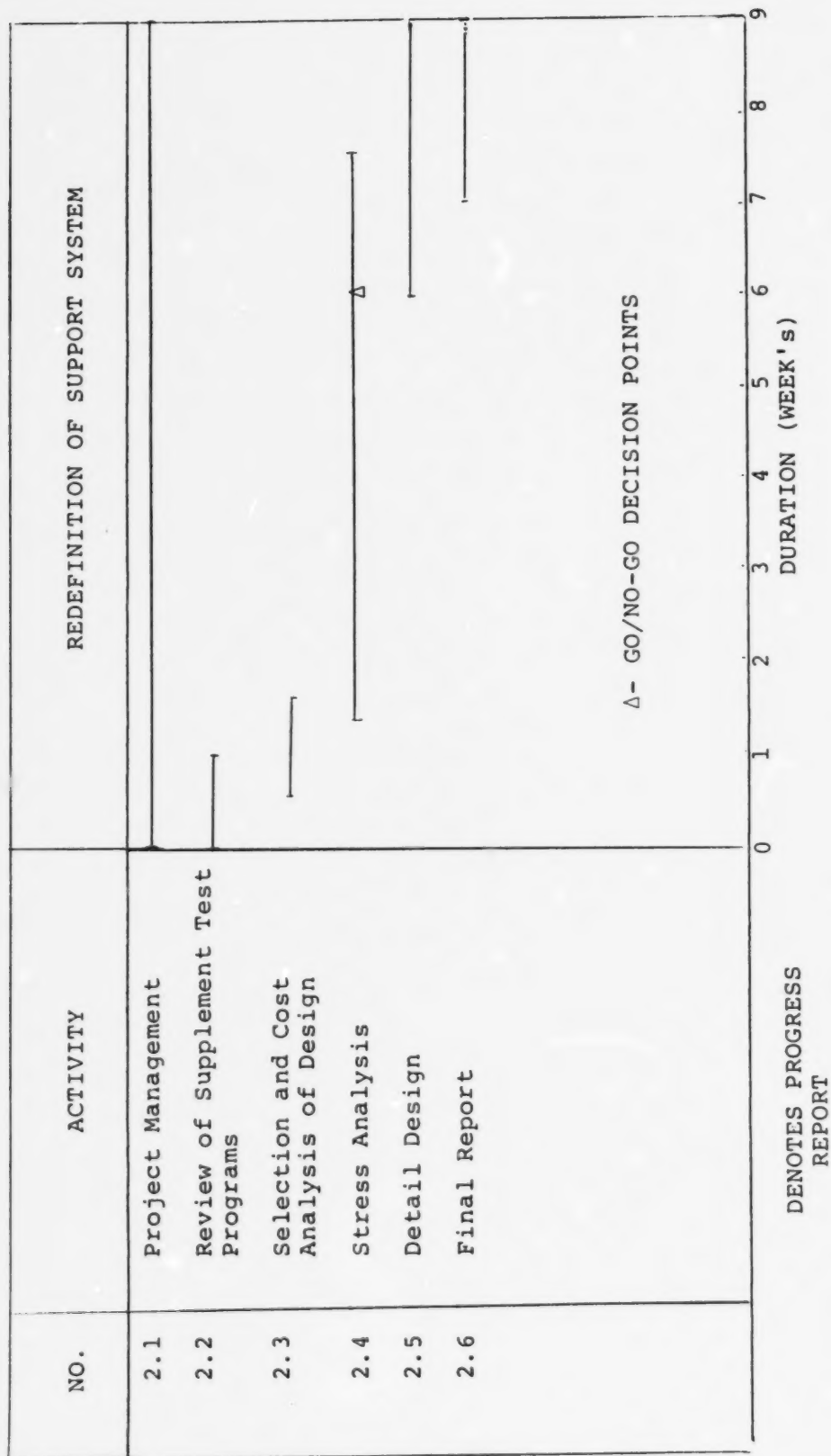


FIGURE F1 - SCHEDULE OF ACTIVITIES

APPENDIX G
FULL SCALE IMPACT TEST PROGRAM

FULL SCALE IMPACT TEST PROGRAM

1.0 INTRODUCTION

A full scale impact test program will be undertaken when a "GO" decision is reached at the conclusion of the redefinition of support system.

The objective of this project is to verify the stress levels in the critical areas, as predicted by the stress analysis, experimentally and to verify the mechanical integrity of the support system and EXPLOSAFE arising from a sudden impact, with induced sloshing.

These tests will be carried out using a full scale instrumented railway tank car equipped with the EXPLOSAFE mesh and the support system. For the impact tests, the test car will be filled with water to 50% capacity of the car or as determined by the sloshing studies as the worst case, but not exceeding the gross weight rating of the tank car. The impact tests will be done at the NRC Railway Laboratory.

After the test car is instrumented and filled with the appropriate quantity of water, the test car would be subjected to a series of impacts against a stationary car with increasing speed increments until a failure prevented further testing or until 5.6 MN (1.25 million lbs) force is developed at the coupling. A thorough inspection of the test car contents and a test data analysis would follow each impact.

The tank car would be provided by Transport Canada and would be used for the impact test as well as the road test program. An arrangement with a shipper to participate in the road test program appears to be feasible.

2.0 ACTIVITIES

The various project activities are shown in Table G1 and Figure G1. An explanation of each activity is given below.

2.1 Project Management

This activity is for the overall coordination, control and management of the project.

2.2 Rail Tank Car Acquisition and Transportation

A tank car will be required to carry out the full scale impact tests. The car will be provided by Transport Canada for the duration of the test program. Although the impact testing program is for a short duration, it is considered practical to arrange possession of the car for a period of approximately twenty seven months since it is anticipated that the same test car will be used for the long term (approximately two year) road test program described in Appendix H. The preliminary cost estimates for shipping and operating a tank car on a regular basis for the two year period indicate the costs are high (in excess of \$300,000). Therefore, there will be a definite cost advantage to consider some sort of participation by a shipping company during the road test program, while using the test car concurrently for shipping LPG and/or A.A. In light of this, a number of shipping companies have been contacted and their respective responses are presented in Table G2. Based on these responses, the following general comments can be made. Firstly, the majority are willing to cooperate on a cost sharing basis if such an arrangement is approved by Transport Canada and their service schedule is not drastically affected. However, concerns were expressed regarding insurance of commodities (due to the presence of EXPLOSAFE), extra cleaning cost and time, weight increase, volume loss, possible contamination and loss of service

time during inspection periods. As a result of the favourable responses in general, it appears feasible to work out a plan with the most favourable shipping company. The shipper would transport the car with the suitable loadings allowing periodic inspection and in return, he would be reimbursed for any cost incurred during tests and inspections. The shipper would also be saving leasing costs which are approximately \$750/month. The other option would be to conduct the test program with no participation from any shipping company. This however, would prove extremely costly if the long term testing proceeded. Transportation costs are typically \$0.71/km (\$1.13/mile) for an empty car. The cost for this activity is for preparation of the tank car for the shipper since there will be no leasing or transportation costs.

2.3 Procurement and Fabrication of Support System

Based on the refined design of the support system, the required materials will be specified and acquired for fabrication. The anticipated facilities that would be used are Procor shop, a qualified mechanical engineering firm (ME)* or some commercial fabricator. The cost estimate presented in Table G1 pertains to the procurement and fabrication costs for a single support system for EXPLOSAFE without the protective skin.

2.4 Installation of Support System

After the fabrication is complete, the support system will be installed either at Procor or at NRC Railway Laboratory. The leased car will be transported to the installation facility for installation of the EXPLOSAFE and the support system. Also if the fabrication site happens to be different from the installation facility then the fabricated material will be transported to the installation site.

* ME will be used to denote any qualified mechanical engineering firm.

2.5 Definition of Test Procedures

Test specifications and procedures for a full scale impact test will be required in accordance with AAR regulations. Therefore a detailed set of test specifications and procedures will be written. It is anticipated that a representative from the NRC Railway Laboratory will also be actively involved in this activity.

2.6 Selection and Procurement of Instrumentation

As a result of the stress analysis, the critical areas will be identified. The instrumentation will be selected in light of that study. The complete instrumentation will involve various types of recorders, pick up devices and photographic equipment. Part of the equipment will be leased for a period of approximately two weeks for use during the test. However, pickup devices such as strain gauges etc. will be purchased. The majority of the instrumentation would be furnished by NRC. The following measurements will be included for each test: (i) Coupler force, (ii) Velocity of the car at impact, (iii) Forces on car, (iv) acceleration of the car.

2.7 Installation of Instrumentation

The various components such as strain gauges, accelerometers, and extensometers will be installed at the specified locations as predicted by the stress analysis studies. This task will either be done by NRC or ME.

2.8 Transportation of Test Car to Test Site

The test car will be transported to the test site for carrying out the impact test.

2.9 Performance of Test and Data Acquisition

The impact test will most likely be conducted at the NRC Railway Laboratory, Ottawa. This facility is well equipped for performing tests of this nature and the personnel involved have expertise in this field.

Due to weather conditions, there are some limitations as to when the test can be done. Since water will be used as the fluid for this test, the test facility is usable only during the months between April and October due to the possibility of sub-zero temperatures occurring outside this range.

The test will be done in accordance with the test procedures outlined in Activity 2.5. It is anticipated that the test car will be used as the hammer car. The test will start with a test car speed of 2 mph and the speed will be incremented by 2 mph for each subsequent test run up to a maximum speed of 14 mph. The test will end when a coupler force of 5.6 MN (1.25 million lbs) is achieved. Data will be recorded during each test. At the end of each test run, a complete inspection of the liner and the support system will be carried out. A high speed film of the car outer shell will be taken during each impact to monitor the distortion of the shell structure of the tank car during the impact.

2.10 Post Test Inspection

At the end of each test run, a complete visual inspection of the EXPLOSAFE liner, the associated support system and the tank car in general will be done to determine if any deformation and/or damage has been sustained. This will also provide a GO/NO-GO decision for the subsequent tests and activities. The visual inspection will be done by utilizing the services of a scuba diver and recording the photographic impressions of the entire inside of the car on a video tape. The outside of the car will also be surveyed to see any evident damage.

2.11 Test Data Analysis

The test data will be analyzed at the end of the complete test. This data will be compared with the predicted results of the stress analysis studies. Particular attention will be paid to the movement of the EXPLOSAFE and the support structure.

2.12 Reporting of Test Results

The results of the full scale impact test will be presented in a report. Work on the project will stop if a drastic failure of the EXPLOSAFE mesh and/or the support system will be evident as a result of these tests and a "NO-GO" decision will be reached. However, if these tests will not indicate any considerable deterioration, the full scale road tests will be performed.

2.13 Dismantling of Support System and Return of Tank Car

If a NO-GO decision is reached at the completion of the impact test, the EXPLOSAFE mesh and the support system will be disassembled from the tank car. The car will then be transported back to Transport Canada. However, if the decision is otherwise, the same car will be used for the road test program.

3.0 COST AND SCHEDULE

The estimated cost of this project is \$143,500.00 and the estimated project duration is twenty one weeks. The details are presented in Table G1 Figure G1.

4.0 IMPLEMENTATION

Reference is made to Table G1. The tank car will be transported by CP or CN to the installation facility. Procurement, fabrication and installation of the EXPLOSAFE and the support system will be done by ME, PROCOR, or some other commercial fabricator. Activities 2.5 to 2.7 will be done by ME and NRC Railway Laboratory. The test car will be transported to the test site either by CP or CN railway. Performance of the impact test will be done by NRC with ME supervision. The post test inspection activity will be carried out by ME, NRC and Ottawa Diving Services and PROCOR. Activities 2.11 and 2.12 will be performed by NRC and ME. The final activity will be carried out at the conclusion of the impact test by PROCOR to inspect the car for damage, etc. If required the interior contents of the test car will be dismantled and made ready for transportation to Transport Canada. This activity will be conducted by ME, NRC and Procor. The transportation will again be done by either CN or CP railway.

5.0 REPORTING

Monthly progress reports will be issued on the status of the project. This will highlight the major project achievements.

TABLE G1
FULL SCALE IMPACT TEST

NO.	ACTIVITY	COST (\$,1000)			TASK ASSIGNED TO
		LABOUR	DISBURSEMENTS	TOTAL	
2.1	Project Management	12.	-	12.0	ME
2.2	Rail Tank Car Acquisition (for 3 month period)	.5	-	.5	Shipping Company, ME, PROCOR, CP,CN
2.3	Procurement and Fabrication of Support System	25.0	17.0	42.0	ME, PROCOR, Other
2.4	Installation of Support System	22.0	-	22.0	ME, PROCOR, Other
2.5	Definition of Test Procedures	3.0	-	3.0	ME, NRC
2.6	Selection and Procurement of Instrumentation	1.0	10.0	11.0	ME, NRC
2.7	Installation of Instrumentation	6.0	.5	6.5	ME, NRC
2.8	Transportation of Car to test Site	-	1.0	1.0	CN,CP
2.9	Performande of Test and Data Acquisition	6.0	2.0	8.0	ME, NRC
2.10	Post Test Inspection	10.0	2.0	12.0	ME, NRC, ODS (*), PROCOR
2.11	Test Data Analysis	4.5	.5	5.0	NRC
2.12	Reporting of Test Results	10.0	.5	10.5	NRC, ME
2.13	Dismantling of Support System and Return of Tank Car	9.0	1.0	10.0	, NRC, PROCOR,CN,CP
	Total =	109.0	34.5	143.5	

*ODS - OTTAWA DIVING SERVICES

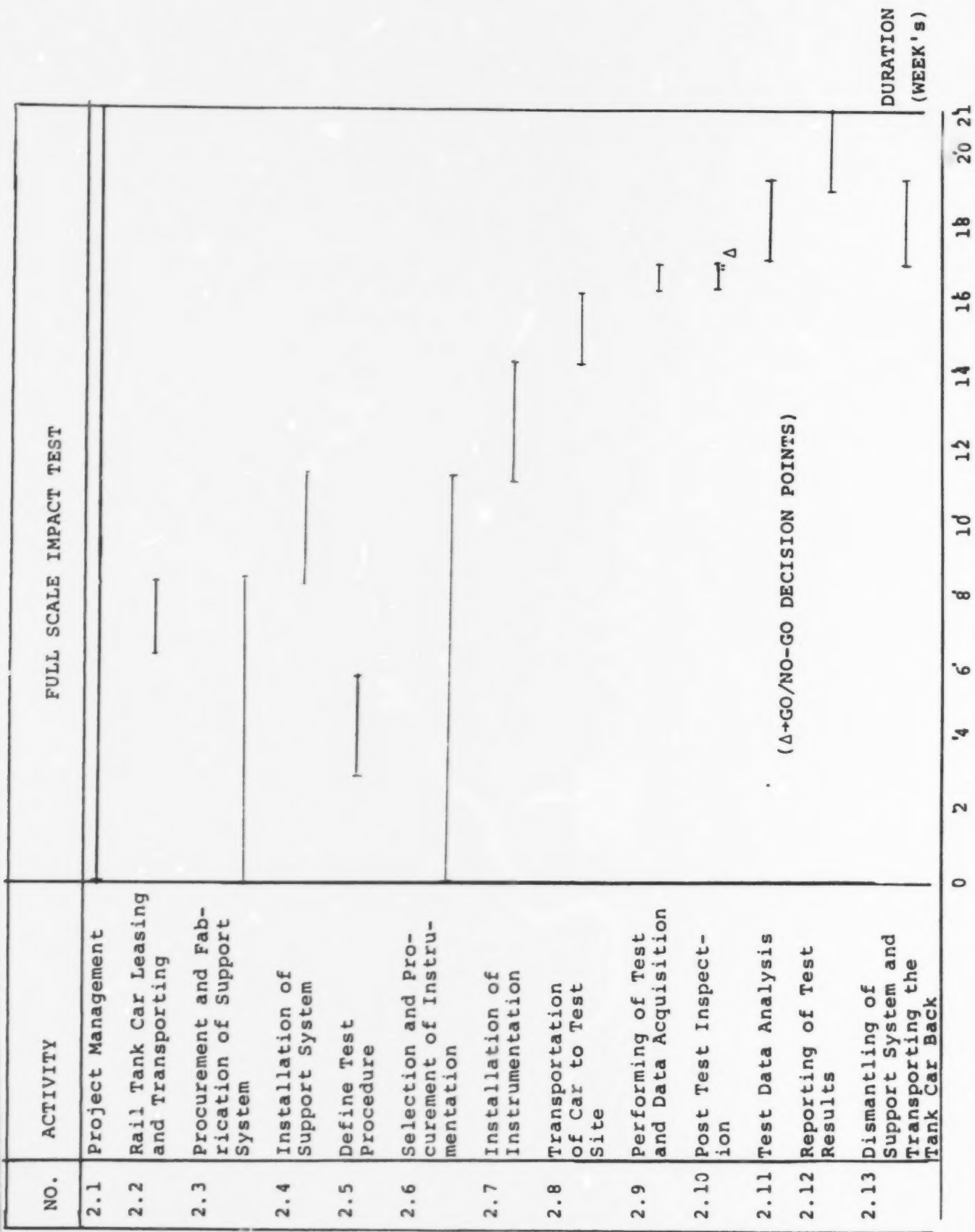


FIGURE G1 SCHEDULE OF ACTIVITIES FOR FULL SCALE IMPACT TEST

TABLE G2
SHIPPER CONTACTS

NO.	NAME OF COMPANY	COMMODITY HANDLED	REMARKS
1.	NITROCHEM. LTD MAINTLAND	A.A.	Small operation, interested but do not have their own cleaning facility.
2.	ELGIN PETROLEUM OTTAWA	LPG	Small operation. Response favourable.
3.	GULF CANADA	LPG	Negative response for the main reason that they do not feel the cleaning process can be done effectively.
4.	CANADA PROPANE	LPG	Favourable response if car is supplied.
5.	AMOCO CANADA	LPG Sublet A.A.	Favourable response.
6.	CJL, SARNIA	LPG, A.A.	Not interested in participating at present but interested in future developments.
7.	DOMO PETROLEUM	LPG	Favourable response. They sublet to A.A. carrier. Edmonton cleaning facility used.

APPENDIX H

FULL SCALE ROAD TEST PROGRAM

FULL SCALE ROAD TEST PROGRAM

1.0 INTRODUCTION

As a result of the "GO" decision at the end of the impact test, a full scale road test (approximate duration of two years) will be undertaken. The objective of the long term road tests will be to expose the EXPLOSAFE mesh and the support system to the actual environmental conditions. This project will be carried out in tasks A and B, running concurrently. Task A will deal with the Mechanical Test Program and Task B will deal with the Corrosion and Cleaning Test Program. The same test car will be used for both tasks. There will be close coordination between the tasks using an overall project coordinator throughout the project.

The total cost of this project is estimated at \$449,300.00 and the estimated time is approximately two years. The breakdown of the cost estimate is given below:

Overall Project Management	= \$ 40,000.00
Travel and Miscellaneous Expenses	= \$ 10,000.00
Task A	= \$192,500.00
Task B	= <u>\$206,800.00</u>
Total	= \$449,300.00 .

OVERALL PROJECT MANAGEMENT

The overall project management will include the management and coordination of activities in tasks A and B for the duration of the project (2 years). Monthly progress reports will be prepared during this project highlighting the status of the various tasks.

TASK A - MECHANICAL TEST PROGRAM

1.0 INTRODUCTION

This task will deal with the mechanical test program involving fatigue failures of the support system components. To perform this test, a tank car will be fitted with the identical installation as for the impact test program. It is assumed that the same TDC tank car is intact and will be used following the impact test. This is a logical assumption since if considerable damage were sustained in the impact test (so that the car was destroyed), further testing would be precluded. The test car will preferably be transported by a shipper carrying LPG and anhydrous ammonia alternately in a normal operational environment. Periodic inspection will be done of the test car every three months for the first year and every six months in the second year.

2.0 ACTIVITIES

The various activities are shown in Table H-A1 and Figure H-A1. Each activity is explained in the following sections.

2.1 Project Management

This activity is for the overall coordination, control and management of the project.

2.2 Rail Tank Car Transporting Arrangements

The tank car used will be the same as used for the preceding impact test. It will be assumed for the purposes of this estimate that it is possible to enlist the cooperation of a shipper of both LPG and anhydrous ammonia. If this were not possible, the cost of this activity would be considerably higher. Dome Petroleum will be used in this analysis as a sample shipper since the Edmonton cleaning facility is used and this would enable WNRE to extract corrosion samples from the car as discussed in later sections. The costs of this activity is primarily the cost of labour to prepare the car for transporting following inspections, etc.

As pointed out in Appendix G, it is felt that Transport Canada could be instrumental in persuading the shipping companies to participate in this program if they can be assured that any rail mishap occurring with the EXPLOSAFE-equipped car will not pose any additional difficulties with regard to the insurance of the car and commodity.

2.3 Define Test Procedures

Test procedures for a full scale road test will be required in accordance with the AAR regulations. A detailed set of test

procedures therefore will be written. It is felt that the representatives from CP, CN (for track selection options), Procor and shipping companies will be consulted for this activity.

2.4 Study of Rail Track Characteristics

Prior to carrying out the road test some information on the rail tracks will be helpful to assess the type of load spectrum a car will be subjected to during travel on a particular track. Therefore, the available data on the various tracks will be gathered from various sources. A preliminary effort in this activity has indicated that the Nuclear Material Management Department of Ontario Hydro was involved in studies of rail tracks for the movements of fuel rods in casks on flat cars. They have been contacted to share this information and the response has been encouraging. Other potential sources of information would be CP and CN railways.

The objective of this activity is to determine vibration spectra for the study of the fatigue failure of some critical components of the support system for a typical track. After selection of the route (which may be dictated by the shipper), the test car will be instrumented with onboard equipment as explained in the next activity.

2.5 On-Board Instrumentation

Once the track is chosen for studying the effects of vibration on the components of the support system, the test car will be equipped with an on-board data acquisition system (DAS). Details

of the various requirements of the monitoring system are given below:

2.5.1 Monitoring System

It is required to monitor the stresses experienced by a tank car, and the resultant mechanical performance of the EXPLOSAFE installation, under actual operating conditions. The resultant data will be used to predict the adequacy of the design and/or refine it to match the measured environment.

The following measurements are required:

- a) strain at 15-20 locations within the tank, eg. on EXPLOSAFE support structure, points of contact between the tank and the structure, etc.
- b) acceleration of the car in 2 or 3 axes
- c) displacement of material (eg. support structure) within the car at critical locations
- d) car velocity and/or time reference as a means of relating above to track and operations

These measurements would be carried out under the following conditions:

- a) normal rail service and car handling, including humping
- b) range of seasonal variations
- c) tank completely or practically filled with liquid propane or anhydrous ammonia
- d) with as little on-road delay as possible

2.5.2 Transducers

Despite the hazards of working with electrical equipment in a propane environment, it will be necessary to sense strain and displacement internally using electrical sensors, ie. strain gauges and linear displacement devices. This is necessitated both because the measuring elements are remote and distributed within the tank, and the effects may occur at high speed (eg. under impulse loads).

Strain is best measured with conventional bonded wire/foil gauges attached to relevant structural members. Problems to be engineered include calibration, operation under fluid and pressure, penetration of tank by signal/excitation loads, and safety.

Displacement measurement using non-contact devices is suggested (eg. linear variable displacement transducers (LVDT) or capacitive sensors), to avoid difficulties with an expected harsh vibration environment, sealing under pressure, and non-restriction of movement by the measuring device. Safety and lead routing considerations will be similar to those of the strain gauges.

Accelerations in 2 or 3 axes are best measured at a designated reference point on the car, eg. centrally, on top or underneath the tank, and fastened to it.

Velocity may be measured either from a pulse pickup applied to a wheel or axle, or using a non-contact, rail-type doppler radar sensor (as used on some locomotives).

2.5.3 Data Acquisition System

Because the tank car will be handled normally, it will be necessary to attach an autonomous, self-contained data acquisition system (DAS) to the car. The DAS will have to provide:

- a) sensor excitation
- b) sensor signal conditioning
- c) recording
- d) power
- e) time reference
- f) environmental protection

Data rate and quantity consideration present difficulties for straightforward analog recording, eg. multi-channel FM tape. To capture transient, maxima, and minima present in a road-excited mode the bandwidth required for some sensors may be high. It may also be necessary to monitor for long periods to define accurate average values. Attempting both simultaneously will produce large volumes of data (eg. 20 megabits/hour) with a correspondingly large data reduction expenditure. Further, the DAS must operate in a power-restricted, harsh environment with minimal attendance.

A recommended approach is to utilize a digital system. The system is software-controlled to provide variable sampling rates (bandwidth), adaptive recording and comprehensive signal conditioning. This would result in manageable data quantities while retaining definition of transient events, and would further provide statistical data, spectra, etc.

Some examples of its use are:

- a) adaptive mode: define conditions which trigger intensive data gathering, eg. velocity changes, accelerations, dis-

placements of support structures. The DAS would normally acquire data on a regular, intermittent basis but be triggered into faster operation when required.

- b) monitor mode: the DAS can be controlled to monitor all sensors continuously but record intermittently, eg. record a strain value once every 5 minutes, along with the maximum and minimum observed in the interval.
- c) normal mode(s): record data at regular intervals selectable through software and/or hardware (wide range of bandwidths and data rates).
- d) statistical mode: record at regular intervals statistics for the interval, eg. number of accelerations for each axis falling within defined bands (0-.1g, .1-.3g, .3-.5g, .5-1g, etc.), corresponding strains, displacements etc.
- e) speed or time-triggered mode: record only when travelling above a minimum speed, and/or record at rates related to speed, or for pre-defined portions of a trip.

Additional benefits of intelligent logging include flexibility to accommodate sensor changes, self-calibration and diagnosis of problems, and power conservation.

The data acquisition system will be compact enough to be housed in a small add-on structure on the test car. It will be sealed against the environment and tampering, and provide some thermal protection.

Powering is expected to require moderate-size, rechargeable or exchangeable batteries in the same or separate container.

Prevention of sparks as ignition sources will be necessary. The cost estimate of this activity presented in Table H-A1 will vary depending on the lading environment, the instrumentation and wiring is exposed. There will be an additional cost if doppler radar is selected for the measurement of velocities.

2.6 Periodic Inspection of Test Car

During the road test, there will be periodic inspection of the EXPLOSAFE mesh and the support system both from corrosion and mechanical integrity viewpoints. This inspection will be conducted every three months for the first year of test operation and every six months for the second year. The inspection site will be the cleaning facility at either Procor, or DOM PET. A GO/NO-GO decision will be made at each inspection.

2.7 Test Data Analysis

The test data recorded by the on-board data acquisition system in Activity 2.5 will be analyzed. To do this, data reduction software will be developed. This data will be compared with the theoretically predicted results. This will also be helpful to detect and to reproduce waveforms, accelerations, and strains for fatigue tests.

2.8 Reporting of Test Results

The results analyzed in Activity 2.7 will be presented in a report. The results presented in this report will be utilized for the fatigue tests of the individual components.

2.9 Fatigue Testing of Components

The critical components of the support systems will be fatigue tested simulating the conditions recorded in Activity 2.5. These will be tested for the life cycle of the tank car.

2.10 Final Report

A final report will be prepared giving details of the complete road task program. Recommendations for future studies will be made, with particular emphasis on the production installation design.

TASK B - CORROSION AND CLEANING PROGRAM WORK PLAN

1.0 WORK PLAN

The work plan in Figure H-B1 shows the basic layout of the program required to conduct meaningful corrosion tests and ensure the development of a workable cleaning process. This work plan shows how the two programs as described in the following section would be integrated into the currently envisaged two year road test schedule.

Accompanying the work plan are activity descriptions which describes each activity and Table H-B1 which gives an estimated cost. Every effort was made to provide cost estimates which were soundly based, however, in some cases due to lack of sufficient background data the cost estimates are purely based on engineering judgement. The costs that are given are split into labour costs and disbursements. The disbursements are combinations of analysis charges, labour charges (not WNRE) rental charges and travel. To present a detailed cost breakdown for each disbursement for this type of preliminary program layout would be pointless as the main objective is to get a feel for the total cost and identify areas of major cost. If EXPLOSAFE was to be pursued to this point then a detailed cost breakdown would certainly be necessary.

2.0 ACTIVITY DESCRIPTIONS

Activity 1-2

Program Initiation

This activity represents the effort required to get the program moving once a

contract was awarded. In addition, it contains the expenses incurred to prepare the detailed proposal.

Activity 2-3

Finalize Contract With PROCOR

PROCOR (Edmonton) has indicated that their facilities could be used to conduct the cleaning tests. Discussions would be required with PROCOR to finalize scheduling and cost details.

Activity 2-4

Fabrication of Corrosion Coupons

This activity would encompass the final design of the corrosion coupons and fabrication. The coupon configuration would be specified and EXPLOSAFE would be contracted to do the fabrication work.

Activity 2-6

Develop and Calibrate UV Visible Spectrophotometer Method

This instrument would be an on-line device to measure the lading concentration in the effluent leaving the tank car. The method of using this instrument for this application would be developed at WNRE.

Activity 3-4

Define Present Cleaning Process

This would involve the taking of laboratory samples during the cleaning process to allow its full characterization. Samples would be taken of the lad-

ing, process water, effluent and residuals from within the car interior. This is quite similar to what was done before but more extensive, including more cars (A.A. and LPG) and samples drawn off at regular times during the cleaning process. It would establish a good statistical basis against which to measure the effect of process changes.

Activity 3-6

Modifications to Process Water Source

It is extremely unlikely that any EXPLOSAFE equipped cars would be cleaned using the present process water. This would require interfacing with PROCOR to establish a workable system of producing clean process water with which to clean the test car (but only on a temporary basis).

Activity 4-5

Corrosion Coupon Installation and Tank Samples

This involves installing the corrosion coupons within the tank car and the taking of samples to characterize the tank prior to operation on the road. These operations would be done after all mechanical tests are completed and immediately before initiation of road tests.

Activities 5-6

Load with A.A. and Operate

7-9

11-13

14-17

Part of the cost incurred with these activities would be common to the mecha-

nical road test program and not fully identifiable with these programs. The only stipulation will be the maintenance of the lading for month periods throughout the road test cycle. This will minimize the required lading sampling to once a month.

Activities 6-7

9-11
20-21
20-25

Cleaning and Corrosion Coupon Removal

After the first 12 weeks of road operation the car will be subject to the first cleaning and at this time the first set of corrosion coupons will be removed. This operation will involve such additional procedures as the taking of laboratory samples, use of the on-line UV Visible Spectrophotometer to define the cleaning parameters and probably some trial and error work in drying the car. This operation would take place at PROCOR (Edmonton). This detailed sampling procedure will be followed for the second cleaning to remove A.A. If no anomalies exist between these two cleanings then no special sampling is planned for the third and fourth cleanings. After the lading switch to LPG after the fourth cleaning, detailed samples will again be taken for cleanings five and six.

Activities 7-10

10-15
15-19
19-22
22-26

Analysis of Corrosion Coupons

These activities involve the analysis of the corrosion coupons after removal from the tank.

26-27

Activities 7-8

11-13

14-16

21-23

25-27

Assess Cleaning Results and Modify
Equipment

This time and expense is allowed for the cleaning results and to prepare procedural and/or hardware modifications for the next cleaning operation. There is no allowance for this after the fourth cleaning for A.A. as it is hoped that by this time the cleaning procedure should be working. An allowance is made following the LPG cleanings in the event anomalies surface intrinsic to LPG.

Activities 13-14

17-18

Cleaning and Corrosion Coupon Removal

The procedure used for these activities is the same for any other cleaning operation except that the sampling program has been largely deleted. Things such as the large number of laboratory samples and on-line sampling would not be done. . If anomalies existed between results of cleanings one and two, then large scale sampling would be re-inserted. Cleaning number four would include the insertion of additional corrosion coupons for monitoring EXPLOSAFE performance in LPG.

Activities 18-20

21-24

Load with LPG and Operate

Part of the cost for these activities would be common to the mechanical road test program and not fully identifiable

with these programs. The only stipulation will be the maintenance of the lading for one month period throughout the road test cycle. This will minimize the lading sampling required to once a month.

Activity 27-28

Final Report

The final report will document all the activities which took place during this test program.

3.0 COST AND SCHEDULE

The estimated cost of this project is \$192,500.00 and the estimated time is twenty five months. The details are presented in Table H-A1 and Figure H-A1.

4.0 IMPLEMENTATION

Refer to Table H-A1. Activity 2.1 will be carried out by a qualified mechanical engineering firm. ("ME" will be used to denote a qualified engineering firm.) Activity 2.2 will be handled jointly by ME, PROCOR, and Dome Petroleum. Definition of test procedures will be mainly handled by ME with inputs from the rail and shipper industries. Activity 2.4 will again be the main responsibility of ME with input from Ontario Hydro, CN and CP Railways. Activity 2.5 will be carried out mainly by ME with NRC installing the strain gauges and performing their calibration. Activity 2.6 will be handled mainly by ME with the help of the facilities of PROCOR, or the shipper. Activities 2.7, 2.8 and 2.10 will be executed by ME. Activity 2.9 will be conducted by NRC.

5.0 REPORTING

A monthly progress report will be presented on the status of the project.

TABLE H-7.1

FULL SCALE ROAD TEST PROGRAM

NO.	ACTIVITY	COST (\$ 1000)			TASK ASSIGNED TO
		LABOUR	DISBURSE- MENTS	TOTAL	
2.1	Project Management	20.0	-	20.0	ME
2.2	Rail Tank Car Transporting Arrangements	2	-	2	ME, PROCOR, DOM.PET, or other Companies
2.3	Define Test Procedures	3	-	3	ME, DOM.PET., or other companies
2.4	Study of Rail Track Characteristics	5	1	6	ME, ONT.HYD., CN, CP
2.5	Onboard Instrumentation and its Design, Fabrication, Installation, etc	50	30	80	ME, NRC
2.6	Periodic Inspection of Test Car	12	10	22	ME, PROCOR, DOM.PET or other companies
2.7	Test Data Analysis	12	-	12	ME
2.8	Reporting of Test Results	5	-	5	ME
2.9	Fatigue Testing of Components	10	20	30	NRC
2.10	Final Report	12	.5	12.5	ME
Total =		131.0	51.5	192.5	

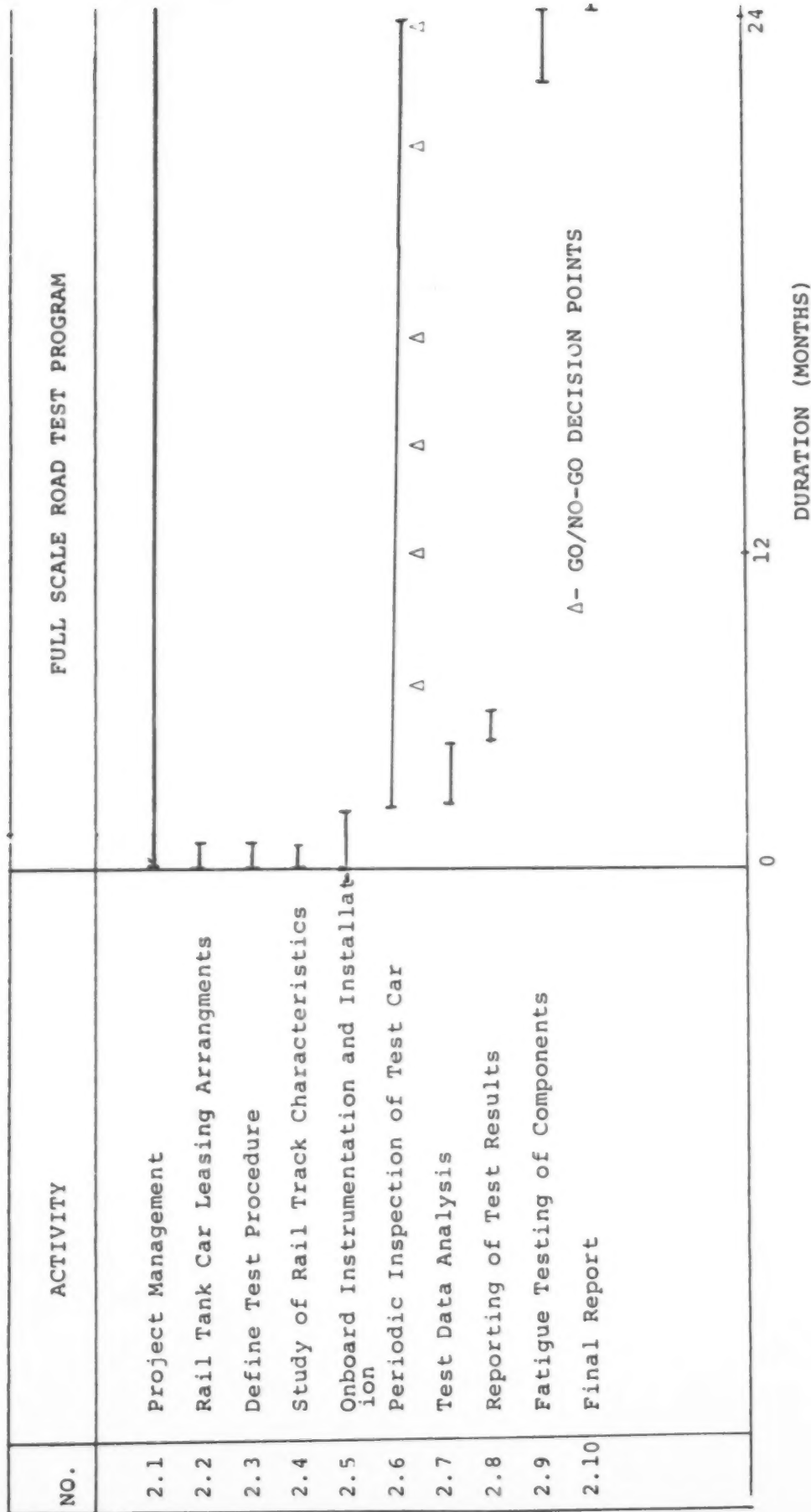


FIGURE H-A1 SCHEDULE OF ACTIVITIES FOR MECHANICAL TESTS

TABLE HB-1

ESTIMATED COST OF CORROSION AND CLEANING PROGRAM

ACTIVITY		--- COST (\$,1000)			TASK ASSIGNED TO
NO.	DESCRIPTION	LABOUR	DISBURSEMENTS	TOTAL	
1-2	Program Initiation	6.4	0.7	7.1	WNRE
2-3	Finalize Contract with PROCOR	0.9	0.5	1.4	WNRE
2-4	Fabricate Corrosion Coupons	2.1	1.0	3.1	ME, WNRE, EXP
2-6	Develop and Calibrate UV Visible Spectrophotometer Method	2.0	-	2.0	WNRE
3-4	Define Present Cleaning Process	2.0	17.0	19.0	WNRE
3-6	Modification to Process Water Source			10.0	WNRE, PROCOR
4-5	Corrosion Coupon Installation and Tank Samples	1.5	2.1	3.6	WNRE, ME, PROCOR 2
5-6 7-9 11-13 14-17	Load A.A. and Operate (Total Cost)	7.2	7.2	14.4	WNRE
6-7	Cleaning and Corrosion	18.0	22.0	40.0	WNRE, PROCOR
9-11 20-21 20-25	Coupon Removal (Total Cost)				

TABLE HB-1 (cont'd)

ESTIMATED COST OF CORROSION AND CLEANING PROGRAM

ACTIVITY		COST (\$,1000)			TASK ASSIGNED TO
NO.	DESCRIPTION	LABOUR	DISBURSEMENTS	TOTAL	
7-10 10-15 15-19 19-22 22-26 26-27	Analysis of Cor- rosion Coupons (Total Cost)	13.8	4.2	18.0	WNRE
7-8 11-13 14-16 21-23 25-27	Assess Cleaning Results and Mod- ify Equipment (Total Cost)			25.0	WNRE, PROCOR, ME
13-14 17-18	Cleaning and Corrosion Coupon Removal (Total Cost)	5.0	5.4	10.4	WNRE, PROCOR
18-20 21-24	Load with LPG and Operate (Total Cost)	14.4	14.4	28.8	WNRE
27-28	Final Report	8.0	1.0	9.0	WNRE
Project Management		12.0	3.0	15.0	

Total 206.8

*WNRE - Whiteshell Nuclear Research Establishment
 ME - A Qualified Mechanical Engineering Firm
 EXP - Explosafe
 PROCOR - Edmonton Cleaning Facility
 PROCOR 2- Oakville

APPENDIX I

FINAL PRODUCTION DESIGN



FINAL PRODUCTION DESIGN

1.0 INTRODUCTION

As a result of all the studies carried out in the previous projects, the design of the support system will be modified (if necessary), to the final production design requirements. The final design will deal with the retrofitting as well as modification of a basic production design.

2.0 ACTIVITIES

The various activities are shown in Table II and Figure II. These activities are described below.

2.1 Project Management

This activity is for the overall coordination, control and management of the project.

2.2 Design Modifications

As a result of the overall study of the project some, modifications of the support system are expected. Therefore, the design will be modified to overcome any shortcomings detected in the system.

2.3 Design Drawings

Based on the modifications of the design and the accompanying changes in the components, detailed design drawings will be produced which will reflect the design modifications.

2.4 Fabrication and Installation Procedures

Procedures for the fabrication and installation of the support system will be detailed in this activity. Any potential problems related to this activity will also be addressed.

2.5 Final Report

A final report will be presented to cover the complete final production design of the support system.

3.0 COST AND SCHEDULE

The estimated cost of this project is \$47,500.00 and the estimated time to complete the project is nine weeks. The details are presented in Table II and Figure II.

4.0 IMPLEMENTATION

All the activities of this project will be handled by a qualified mechanical engineering consulting firm except Activity 2.4 which will involve input from PROCOR a car designer/manufacturer/leaser.

5.0 REPORTING

A progress report will be submitted on the status of the project is a period of one month following project initiation.

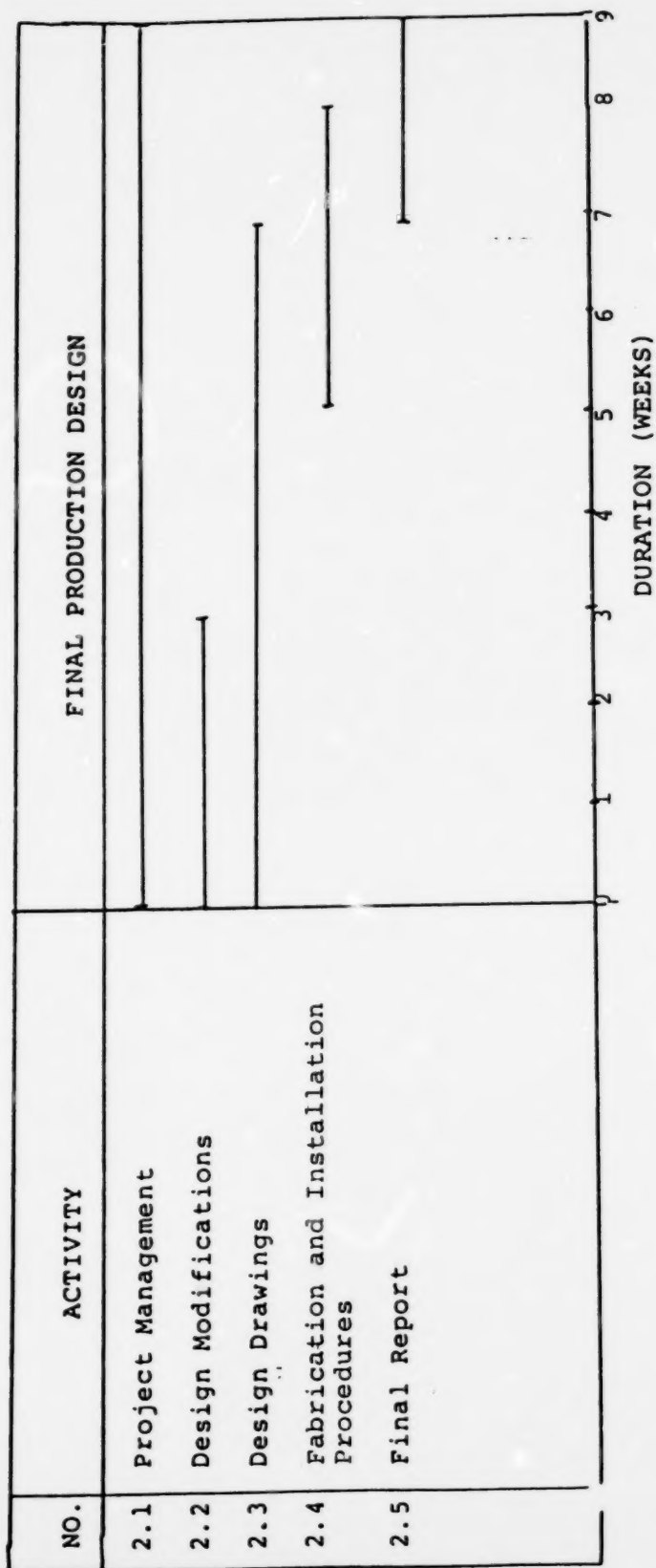
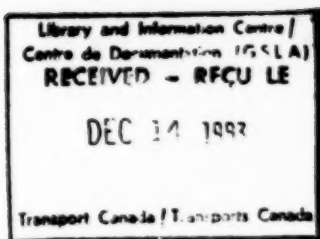


FIGURE 11 SCHEDULE OF ACTIVITIES FOR FINAL PRODUCTION DESIGN

TABLE II
FINAL PRODUCTION DESIGN

NO.	ACTIVITY	LABOUR	COST (\$, 1000)		TASK ASSIGNED TO
			DISBURSEMENTS	TOTAL	
2.1	Project Management	5.0	-	5.0	ME*
2.2	Design Modifications	5.0	-	5.0	ME
2.3	Design Drawings	20.0	-	20.0	ME
2.4	Fabrication and Installation Procedures	5.0	-	5.0	ME, PROCOR
2.5	Final Report	12.0	.5	12.5	ME
TOTAL =		47.0	.5	47.5	
*ME - A Qualified Mechanical Engineering Firm					

CA1
DTC 801
83
E83
C.2



POOR

QUALITY

ORIGINAL